Stream Rehabilitation Using LOD Placements and Off-Channel Pool Development

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FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multi-disciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests (Research Branch), and the B.C. Ministry of Environment (Fisheries Branch). Participating agencies include Forestry Canada (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

Program results are published through the B.C. Ministry of Forests, Land Management Report series, as well as in papers presented at symposiums, conferences, and through technical journals.

For information about the program contact Ministry of Forests, Research Branch, 31 Bastion Square, Victoria, B.C. V8W 3E7.

Stream Rehabilitation Using LOD Placements and Off-Channel Pool Development

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SUMMARY

Evaluation of 23 stream rehabilitation structures and 10 ponds created with explosives in off-channel areas indicated that operational level rehabilitation increased the extent and diversity of habitat suitable for fish. Placement of single and multiple log structures and the creation of off-channel pools significantly increased summer and winter habitat in the study streams. Juvenile salmonid habitat improved substantially at large organic debris (LOD) sites through increases in pool area, the number of pools, pool depth, and cover. Construction costs of LOD structures averaged $341 (1986 $Cdn) per log and $492 for each blast pool. Restoration guidelines presented include candidate stream selection, site frequency and selection, vertical and horizontal placement design, anchoring, equipment requirements, post-construction activities costing, and log selection.

Engineering assessment of the structures showed that use of cabling techniques and logs buried into the channel substrate were sufficient to stabilize and anchor logs with respect to anticipated flood flows. However, development of scour pools and sediment storage areas had not reached expectations after a 1-year post-construction evaluation period. This was attributed to lower than expected winter floods in the 1st year. The single log structures generally performed better than the multiple log structures, with sediment storage generally occurring upstream and scour pools forming downstream.

Geomorphic evaluation of the sites found distinct pool-riffle sequences and larger, more extensive sediment bars occurring after construction. Depth variability increased at LOD sites and cross-sectional profiles showed that log placements precipitated both large and small scale gravel accumulations. Number of gravel storage sites generally increased and compartment size decreased with LOD site construction in all study streams. Surface texture data also showed an increase in sediment size and variability, suggesting greater sorting at LOD structures.

As well, LOD structures did not change spawning gravel composition with respect to D50, D <3.36 mm and <0.85 mm fractions, Fredle index, permeability, and dissolved oxygen as a result of construction. Gravel scour at LOD sites over the 1986-87 winter period was minimal, averaging 7-11 cm, reflecting low flood discharges over the study period.

Juvenile salmonid habitat characteristics improved substantially at LOD sites. Pool habitat increased with LOD site construction in all streams. Total cover and winter cover similarly increased. Improvements in habitat relative to controls was enhanced in Macmillan and Southbay Dump creeks, which were more severely damaged by debris torrents than Sachs Creek. Habitat at LOD sites in Sachs Creek compared favourably to gabion sites constructed in an earlier study. Off-channel pools in Bonanza Creek tributary were subject to dewatering before and after pool construction. Loss of vegetation cover through blasting was more than compensated by increases in deep water habitat created in the pools.

Juvenile salmonid response to the LOD structures was positive, with substantially increased densities after LOD site construction in both Macmillan (from 1.0 to 210%) and Southbay Dump creeks (from 13 to 194% of control densities, respectively). Stocks in Sachs Creek were variable after construction compared to gabion and control sites. Juvenile densities in blast pool sections of Bonanza Creek tributary similarly increased substantially after construction (from 61 to 485% that of control sections).

Short-term impacts of construction were acceptable given the severity of the damage induced by mass wasting and prognosis for recovery. Suspended sediment levels immediately downstream of construction ranged from 1330 to 1860 mg/L total solids, and decreased rapidly to 37-38 mg/L, 100-200 m downstream within 1 hour post-instream activity. Settleable sediments rapidly decreased from 0.33-0.40 gm/cm^2 at 25-30 m downstream of construction, to 0.01-0.04 gm/cm^2, 80 m downstream. Impacts of equipment access were minor, and all disturbed areas were grassed following construction.

Owing to the benign winter flows which occurred over the 1-year study period, it was not possible to test fully the durability of the structures and determine the final site characteristics that would be achieved. Notwithstanding testing at higher flood flows, evaluation of the structures after the first winter suggests that single logs, placed horizontally diagonal to the stream and vertically oblique to the bed, were the most successful structures tested. Single logs were easy to place, least difficult to stabilize, and lowest cost to develop. Furthermore, they posed no difficult engineering problems and provided the greatest flexibility for permitting changes in the field. However, single logs resulted in the least complex habitat developed. Higher complexity could be achieved by the addition of root wads cabled downstream of the logs. The log arch structures appeared to provide equally good habitat, although they were 2-3 times more expensive to construct, vulnerable to jamming, and, because of construction limitations, rarely achieved sediment storage characteristics.

An interim survey conducted in 1989 after a series of high flows indicated extensive pool and sediment storage area development at the log emplacement sites. Stream averages of 4.4 - 20.6 m^2 per log pool area and 18.1 - 30.1 m^2 per log sediment storage area were associated with the structures. The LOD emplacement durability was high, with 75-80% of the logs remaining unmoved since construction. However, 21-50% of the logs were underscoured and 0-15% of the logs were buried. Streambank erosion was minimal, averaging 1.9-7.7 m per log. The blast pools at both Macmillan and Southbay Dump creeks were largely filled in with sediments.

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PREFACE

This study was undertaken as a Research and Development project funded by Supply and Services Canada and Fisheries and Oceans Canada to develop stream rehabilitation options suitable for use in small, higher gradient streams damaged by mass wasting. The study tested three techniques including: 1) large organic debris (LOD) placements consisting of single logs; 2) multiple-log structures (LOD arches); and 3) side-channel ponds created with explosives. The study was undertaken by a multi-disciplinary team of specialists having expertise in salmon biology, geomorphology, and hydraulic engineering. Consultation between the team members was ongoing during design, construction, and evaluation stages.

Because of funding criteria, the project was designed as a 2-year study commencing in 1986 and concluding in 1987. This limited the post-construction evaluation of the structures to habitat alterations generated after the first winter of construction and only one winter of stream flows. As nature would have it, the winter of 1987 was relatively benign. Winter flows were unseasonably low and did not achieve flood heights sufficient to alter the sites as great as anticipated. In 1989, a series of very high floods occurred in the study streams which provided an opportunity to briefly examine the condition of the structures. The results of this survey are reported in Appendix 4. In addition to these evaluation efforts, a follow-up study, replicating the original surveys and including estimation of smolt production, was initiated by the Fish/Forestry Interaction Program (FFIP) in 1989. This study is underway and will be concluded following the 1990 downstream smolt migration and summer habitat evaluations.

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Major funding of this project was through Canada Departments of Supply and Services and Fisheries and Oceans. Fletcher Challenge Ltd., Sandspit Division, provided additional support and co-operation required for the success of the project.

Scientific authorities for the project were Mr. M. Brownlee and Mr. J. McNally, Department of Fisheries and Oceans, Vancouver, B.C. Overall project management was by Mr. V.A. Poulin, principal, V.A. Poulin & Associates Ltd. Mr. D.B. Tripp, senior biologist for the project, was responsible for construction, field operations, and data analysis. Mr. D.L. Hogan, fluvial geomorphologist, provided assessment of the channel response to the rehabilitation structures. Mr. H.D. Klassen, biologist, supervised collection of biological field data. Mr. V.A. Poulin and Mr. H.D. Klassen compiled and edited the final report. Technical assistance for the project was provided by Mr. J. Werring, Mr. D. Holm, Mr. W. Grant, Mr. G. Kendall, and Mr. J. Lockard. Analysis and interpretation of gravel quality data was provided by Dr. M. Church, University of British Columbia. The engineering component of the study was undertaken by Mr. D.D. McConnell, Hay & Company Consultants Inc. Mr. P.A. Slaney, Fisheries Branch, Ministry of Environment reviewed an earlier draft. Heavy construction was contracted to AWM Contracting, Bob's Heavy Duty, and Mr. F. Kendall for skidding logs to the sites; to Ignas Contracting for backhoe placement of the logs; and to Mr. H. Hampton for conducting the blasting. Maps were drafted by Mr. D. Holm, V.A. Poulin & Associates Ltd.

1 INTRODUCTION

The need to develop techniques to restore fish habitat in streams affected by land-use developments has been identified in recent years (Hall and Baker 1982; Hassler 1981), yet most stream rehabilitation efforts have focused on relatively low gradient or gravel deprived streams. On the Queen Charlotte Islands, mass wasting is the dominant geomorphic process acting to erode unstable terrain. Triggered by either logging or natural events, mass wasting in the form of debris slides, debris flows, and torrents can travel several kilometres downstream (Gimbarzevsky 1988) into productive stream reaches (Tripp and Poulin 1986a).

Once mobilized, debris torrents can cause extensive damage to fish habitat by scouring steeper gradient sections and depositing large volumes of sediment and debris in lower gradient areas downstream. In stream reaches directly affected by debris torrents, the principal mechanisms responsible for loss of fish habitat are changes in the orientation of large organic debris (LOD) and resultant alteration of stream sediment storage and routing characteristics (Hogan 1986). In streams where LOD is the dominant hydraulic control, its orientation – which is predominantly diagonal or perpendicular to the channel – is responsible for habitat development. This position maximizes the width and depth variability, size and frequency of pools, and stability of sediment storage sites introduced into the channel by debris. In streams directly affected by torrents, debris shifts from diagonal to parallel positions as logs are pushed from the path of the slide. This results in an overall simplification of the channel. This reduction in channel complexity reduces the amount and diversity of fish habitat (Tripp and Poulin 1986a). Debris-controlled pools are replaced by coarse, bouldery substrates. These lack the hydraulic effectiveness of LOD in storing and retaining instream gravel deposits, and in creating winter cover in the form of deep, LOD complexed pools. These effects of mass wasting have the greatest impact on fish populations in streams where overwinter habitat is restricted to the mainstem. In some severely affected Queen Charlotte Islands streams, winter cover was reduced by 86% and corresponding overwinter survival was less than 2% compared to 17% in more stable stream environments.[1]

Careful replacement of LOD in stable configurations can effectively reverse the process of debris loss by restoring the frequency of natural hydraulic controls and controlling channel scour and deposition characteristics. Several debris configurations were tested and combined where possible with off-channel pools development. Studies undertaken by the Fish/Forestry Interaction Program (FFIP) from 1982 to 1984 identified several options for rehabilitating the characteristically steep streams that drain much of the active logging area in the Queen Charlotte Islands. In these earlier studies, techniques involving placement of LOD were shown to significantly improve habitat diversity in torrented channels toward levels noted in undamaged streams (Hogan 1986; Tripp 1986; Tripp and Poulin 1986a). Off-channel pool areas were similarly found to be important in contributing to fish overwinter survival (Tripp 1986), and thus were viewed as complementing LOD restructuring where channel width and floodplain characteristics permitted their use.

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[1] Tripp, D.B. and V.A. Poulin 1989. The effects of logging and mass wasting on salmonid juveniles in Queen Charlotte Islands streams. B.C. Min. For. In prep.

The present study began in May 1986 with the purposes of further developing and testing aspects of log placement strategies and of applying engineering principles in the design and construction of the structures. Off-channel pools were also tested in active floodplains of torrented channels and in a stable tributary of a larger watershed degraded by widespread mass wasting. Engineering guidelines were developed so these techniques could be applied in other stream rehabilitation projects.

The log structures tested consisted of several generic types. Logs placed diagonal to the channel and angled into the bed were designed as simple cross-stream obstructions for stabilizing upstream and downstream gravel wedges and scouring deep-water pools in both central and lateral channel positions. Where lengths of logs were insufficient to span the entire channel, multiple-log steps were created by cable-lashing smaller log pieces together. A log "arch" consisting of three logs, two of which formed an upstream V angled into the bed, were developed to test centre channel scour characteristics and adult holding pool formation.

Site selection and pre-construction evaluation were completed by July 15, 1986, to permit construction during the summer low-flows from July 15 to August 15, 1986. Project design required post-construction monitoring of channel response and effectiveness be completed by September 1987. Pre-construction and post-construction evaluation involved field measurements of stream cross sections, thalweg, size and configuration of sediment storage characteristics; and quantification of summer and winter fish habitat cover characteristics and relative use by fish. The above data were complemented by complete aerial photography coverage of study sections 1 month and 1 year after construction. Downstream smolt and fry trapping was beyond the scope of the current study. Thus, evaluation of the structures is based on amount and quality of physical habitat created within 1 year following construction.

Specific objectives of the study were to:

1. determine optimum configurations of LOD required to create and maintain new spawning and rearing areas in debris torrented streams;
2. assess the effectiveness of re-introducing LOD to stabilize ordinarily mobile sediment deposits in debris torrented streams;
3. compare the effectiveness and potential benefits of gabions with similar structures constructed out of LOD;
4. determine whether juvenile salmonids will overwinter in newly created off-channel ponds and whether survival rates and potential smolt production are cost-effective;
5. undertake an engineering assessment of the hydraulic characteristics associated with various LOD placement techniques, of the forces involved, and of the degree to which the response of the river to LOD placements can be predicted; and
6. prepare a set of guidelines for the use of LOD, based on the experience and observations from the field work.

2 STUDY AREA

The study streams included in the study are shown in Figure 1 and characterized in Table 1. These included:

1. Macmillan Creek
2. Sachs Creek
3. South Bay Dump Creek
4. Bonanza Creek Tributary

TABLE 1. General characteristics of the study streams

Stream	Length (km)	Area (km^2)	Geology[a]	Precip.[b] (mm)	Flow range[c] (m^3/s)	Landuse[d]
Macmillan	4.9	6.2	Sedimentary	≥ 3665	.04 - 21[b]	LT, 1978/79
Southbay Dump	3.2	3.9	Sedimentary	≥ 3665	.04 - 13[b]	LT, 1978
Sachs	11.0	19.0	Sedimentary	>3665	.3 - 65[e]	L, MW, T
Bonanza	16.0	88.5	Basalt	≥3665	NA	L, MW

[a] Sutherland Brown (1968).

[b] Hogan and Schwab [1990].

[c] Instantaneous discharge.

[d] **L** - Logged, **LT** - Logged, Torrented, **MW** - Mass Wasting in upper watershed, **T** - Torrented instream.

[e] Klassen 1984.

2.1 Macmillan Creek

Located on northern Moresby Island, Macmillan Creek is a 4.9 km long first-order stream draining a 6.2 km^2 watershed. Average precipitation in the Macmillan watershed exceeded 3600 mm per year, with flows ranging from about 0.4 to 21 m^3/sec (Hogan and Schwab [1990]). The lower 500 m of stream was first logged in 1946, but it was not until the early 1970's that the upper watershed was logged. By 1984, 65% of the watershed was clearcut harvested. In 1978, a major debris torrent sluiced the channel from its headwaters to the stream mouth at Skidegate Channel, following the path of a still larger torrent reported to have occured in the 1950's. Post-torrent LOD volumes were low, with riffle accounting for 70% of the available summer habitat in 1982. Subsequent channel downcutting has resulted in channel substrates shifting from coarse gravel/cobble to a predominantly coarse gravel/boulder substrate with small, isolated debris jams present along the old torrent track. Overwinter cover before construction ranged from 1 to 19% of stream area in the lower reaches of Macmillan Creek (Table 7).

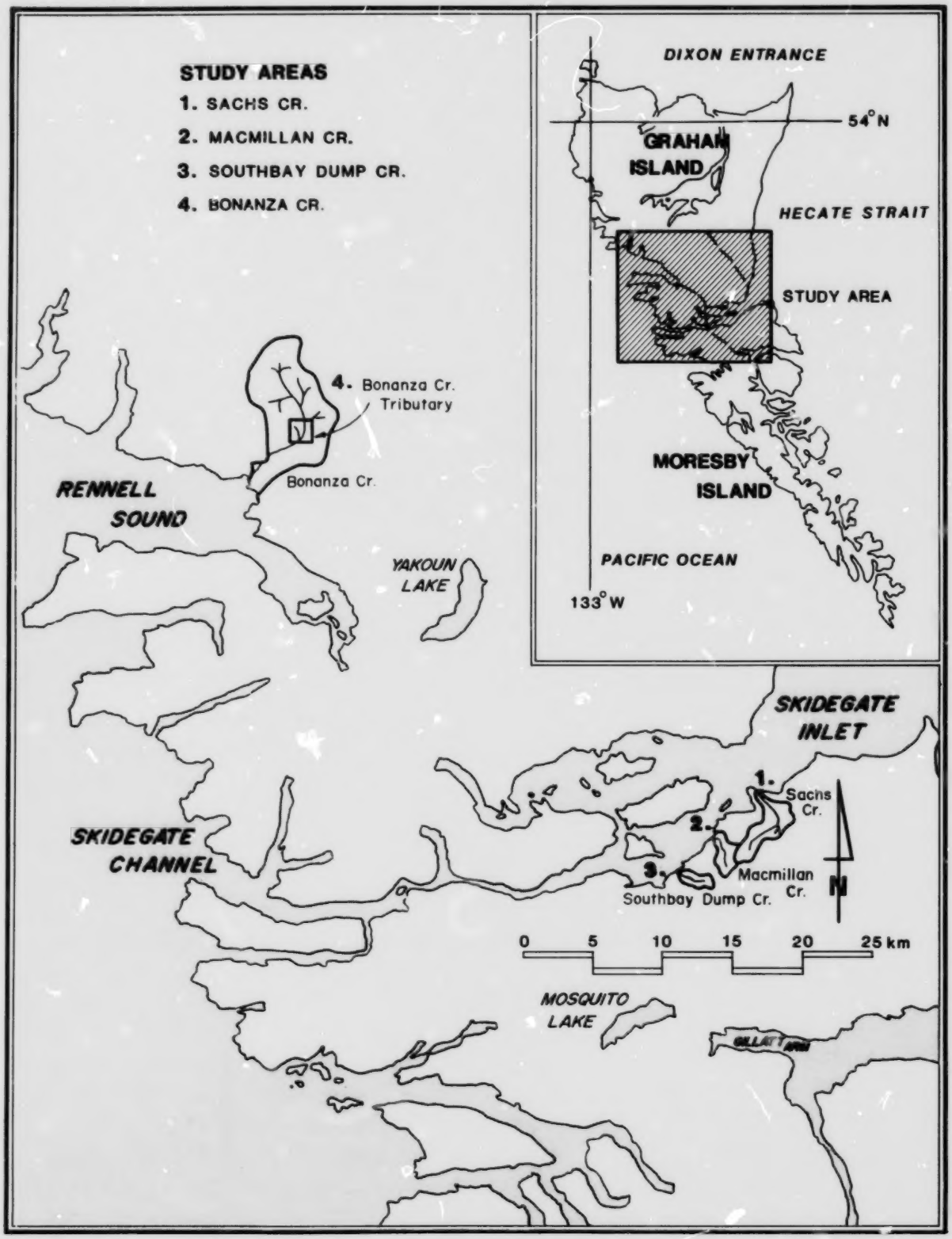

FIGURE 1. Location of the study streams.

Rooted channel width is 20-30 m, with wetted perimeter in summer ranging from 1.0 to 3.0 m. Riparian vegetation is dominated by red alder (*Alnus rubra*), with small clumps and patches taking increasingly greater roles as overhanging vegetation each year since torrenting. Adjacent stands of second-growth forest consist of western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Sitka spruce (*Picea sitchensis*). Extensive deposits of gravel in the lower 200 m of stream represent remnants of unconsolidated materials transported downstream by the 1978 torrent and post-torrent deposition of fluvial gravels from upstream source areas, and of material scoured from within the channel since torrenting. By 1986, the upper 200-500 m of stream had down-cut to a scour resistant armour layer consisting of a boulder/cobble substrate.

The stream supports populations of chum and coho salmon, but escapements over the last 5 years have generally remained below 25 to 30 adults. However, in 1986 a strong run of approximately 300-600 chum salmon and 50 pink salmon entered the stream. Downstream smolt trapping undertaken in 1984 suggested coho overwinter survival was less than 2% compared to a high of 17% in more stable streams examined (Tripp and Poulin 1986). Pre-torrent escapement levels are unknown.

2.2 Southbay Dump Creek

Southbay Dump Creek is a 3.2 km long stream draining a 3.9-km^2 basin on northern Moresby Island. Mean annual precipitation in the basin is estimated to be 2000-2500 mm, with less than 15% falling as snow (Hogan 1985). Mean monthly summer flows range from 0.04 to 0.09 m^3/sec, with winter peaks averaging 1.36 m^3/sec (Tripp 1986) and ranging to 13 m^3/sec (Hogan and Schwab [1989]). The lower reaches of Southbay Dump Creek watershed were logged from 1961 to 1980. By 1985, approximately 85% of the watershed was logged. In October 1978, a major torrent sluiced the entire steam channel. In 1983, a torrent-like flood again restructured the stream by mobilizing large volumes of gravel after breaking through several log jams formed by the 1978 torrent. Habitat conditions before rehabilitation indicated overwinter cover was minimal (7-17% of stream area; Table 8).

The wetted widths of the rehabilitation reach averaged 2-3 m and followed a relatively straight riffle course over a 20 m wide floodplain. Floodplain areas were dominated by extensive deposits of unconsolidated gravels lacking well-defined steam banks. Vegetative cover within the channel consists of 1- to 6-year-old alder and second-growth redcedar, hemlock, and Sitka spruce in overbank areas.

There are no salmon escapement records for Southbay Dump Creek, but before torrenting, salmon escapement levels were reputed to have been "reasonably good" for both chum and coho salmon, the two dominant species. Post-torrent records are equally deficient, although surveys in 1982 indicated 19 coho and 4 chum adults in the stream (Tripp 1986).

2.3 Sachs Creek

Sachs Creek drains into Skidegate Inlet on the northern side of Moresby Island approximately 10 km east of Macmillan Creek. The stream is 11 km long and drains a 19-km^2 watershed. Mean annual precipitation is similar to that in Macmillan and South Bay Dump creeks. Summer flow averages about 0.3 m^3/ sec, with stormflow discharges reaching approximately 65 m^3/ sec during winter (Klassen 1984).

Throughout the study reach in the downstream 700 m, Sachs Creek width averages 5-7 m and follows a relatively straight course between well-defined 1.0 m high stream banks. Vegetative canopy is approximately 100% and consists of old-growth alder, redcedar, hemlock, and Sitka spruce.

Approximately 60% of Sachs Creek has been logged. Leave strips along both banks in the lower 2 km of stream provided a buffer from logging in the early 1960's. Logged areas in the lower watershed were completed by 1980, after which logging concentrated in the upper watershed. Mass wasting is present throughout the watershed. In 1974, a major road failure at the head of the watershed torrented the upper two-thirds of the mainstem channel, stopping just upstream of anadromous fish habitat. Evidence of channel alterations resulting from sediment release is apparent in the lower stream channel in the form of lateral channel migration and reappearance of LOD uncovered by recent channel downcutting. Overwinter habitat values were relatively high before rehabilitation, with values ranging from 11 to 29 % (Table 6).

Sachs Creek supports chum, pink, and coho salmon. Pink salmon "even year" escapements have historically ranged from 400-30 000, with a mean of about 4600 (Klassen 1984). Chum salmon were less abundant, with historic ranges of 25-1500 adults. Over the past decade, escapements of pink and chum salmon have from ranged about 3000 to 4000 and 200, respectively. Coho escapement estimates are uncertain, although juvenile standing crops in summer suggest Sachs Creek supports reasonable populations.

2.4 Bonanza Creek Tributary

Located on the west coast of Graham Island, Bonanza Creek is a 16 km long stream which drains an 88-km^2 watershed. Mean annual precipitation is about 3600 mm/yr (Hogan 1986).

Bonanza Creek was first logged in 1975 and activities continued through 1982. The stream was originally logged with protective buffer strips, but extensive blowdown has since forced salvage operators to log to the stream channel throughout the lower stream reaches. The watershed is logged on only one side of the watershed. Approximately 11% of the watershed was logged by 1982. Extensive mass wasting in the form of debris slides, flows, and torrents has occurred throughout the watershed both in logged and unlogged areas (Rood In press).

Bonanza Creek flows through a 300-500 m wide valley, surrounded by steep, marginally stable slopes. The watershed is dominated by old-growth forests of western redcedar, western hemlock, and Sitka spruce. Mainstem Bonanza Creek follows a well-defined 20-40 m wide channel with banks of 1.0-1.5 m.

An unnamed tributary to Bonanza Creek was selected for testing off-channel pool construction using blasting techniques. The tributary follows a 0.5-1.5 m wide, meandering course across the Bonanza Creek flats before joining the mainstem 15 km upstream from the mouth. The tributary drains a steep, south-facing hillside that was logged in 1978 - 1979. Bottom substrates are dominated by alluvial sands and clays. The tributary was representative of small, flood plain channels draining into third- and fourth-order west coast streams. Overwinter habitat values were relatively high before rehabilitation, ranging from 21 to 29% of reach areas (Table 9).

Escapement records available for Bonanza Creek from 1970 to 1977 suggest even-year pink salmon numbers may have ranged as high as 70 000 (Marshall *et al.* 1978). Coho were not listed, but are present throughout the system. Juvenile coho salmon and Dolly Varden char use the off-channel tributary habitat channel, but low flows may limit access to the tributary in some years.

3 STUDY DESIGN AND METHODOLOGY

The rehabilitation sites were first identified during a reconnaissance, and then subjected to an extensive pre-construction evaluation in spring 1986. This was followed by construction during summer 1986 and the first of two post-construction evaluations. The final post-construction evaluation was completed 1 year following construction in August 1987. Detailed construction procedures for each site including placement, location, excavation requirements, site-specific positioning of logs, anchoring, and back filling requirements are described in Appendix 1.

3.1 Site Reconnaissance and Identification

At total of 20 LOD placement sites were constructed to enable evaluation of a variety of structural configurations and stream channel responses. Macmillan Creek was selected as the principal study stream. Macmillan Creek was torrented in 1978 and pre-construction channel characteristics indicated a significant lack of overwinter habitat for juvenile salmonids. The stream was also close to Sandspit and had easy access. The LOD spacing in non-torrented channels suggested that using an inter-structure spacing of two to three bankful widths (Hogan 1986) was required to re-establish pool/riffle sequences in channels the size of Macmillan Creek. This required close to 1 km of stream channel for the desired number of structures to be tested. However, only the lowermost 600 m were suitable for rehabilitation, accommodating 12 LOD placements. A comparable stream (Southbay Dump Creek) was identified to supplement the study with a further six LOD placements. Use of Southbay Dump Creek had the additional benefit of an existing data base, compiled during an earlier study to develop instream rehabilitation structures (Tripp 1986).

Study sites selected for the log arch/gabion comparative analysis were those used previously for the FFIP gabion study in Sachs Creek (Klassen 1984). Two former control sites at 1% gradient from the gabion study were designated as LOD arch sites and two others remained as controls. Two years of background data made these sites particularly attractive for this study. A total of four log arches matched the four gabion weirs.

Sites for the pool development study were located on a tributary to Bonanza Creek where an exploratory FFIP pond development project was conducted (V. Poulin, file data). Six sites downstream of the 1982 pond were selected for pond development. Experimental reaches alternated with control reaches. Four blast sites were also selected in side channels of Macmillan and Southbay Dump creeks to determine whether off-channel habitat could be created on active debris-torrented flood plains consisting of gravel substrates.

3.2 Pre-Construction Site Evaluation

A range of geomorphic and fisheries studies were undertaken before rehabilitation so that channel conditions could be documented. They included:

3.2.1 Geomorphology studies

Fluvial geomorphology studies were designed to characterize the morphology of each channel before log placement, and to document channel changes after 1 year. The following methods were used in the field and later during data analysis.

Longitudinal profiles

Longitudinal profiles were surveyed to evaluate changes in channel elevation over time. Field procedures followed Hogan (1986) and are shown in Figure 2. Distance along the thalweg was determined by either tacheometry or by direct reading of a survey chain. Elevations were calculated by relative differences and these were based on bench marks established at the beginning of the project. Survey points along the thalweg were determined by primary morphological units (pools, riffles, bars); the survey separated these features and included intermediate points (Figure 2).

All data were stored on computer files. A commercial spreadsheet program was then used to reduce the data to relative elevations and distances. These were plotted by computer.

To assess the depth variability of each reach, a linear regression model (appropriate over short reaches) was fitted to the data and then the residuals of the actual long profile around the model were evaluated. The standard error of estimate (actually the standard deviation of the residuals) quantifies depth variability along the reach.

In-channel topography and bed configuration

Channel features were characterized through a variety of engineering survey and photographic techniques. In all study reaches monumented cross-sections were established at intervals ranging from 7.5 to 10 m separation. Cross-sectional transects (elevation and distance) were conducted before, immediately after, and 1 year after log placement. Low-level air photographs, obtained from altitudes ranging from 8 to 35 m, provide additional channel details between cross-sections and adjacent to longitudinal profiles. These photographs and survey data were also used to calculate the volume and number of storage sites within each reach.

All cross-sectional data were stored on computer files, and relative elevations (bench marks tied to longitudinal profile reference elevations) were calculated and plotted by commercial computer programs. Large scale topographic maps (1:250 and 1:500) were drawn according to these data. Pool and riffle water depth contours, obtained from field surveys and air photographs, were added to the maps.

Chronological sequences of cross-sections were plotted as overlays and several measurements were made on each. These included the area and apparent depth of sediment both eroded and deposited along each transect over the 1-year period. Subtracting the total area eroded from the total area deposited provides a measure of net channel aggradation or degradation, over distance along the reach for the study duration. Multiplying the total areas by the mean distance separating the cross-sections yielded a reach-averaged estimate of sediment transfer. Sediment storage sites were delineated on the large-scale maps (based on low-level air photographs and direct field measurement)

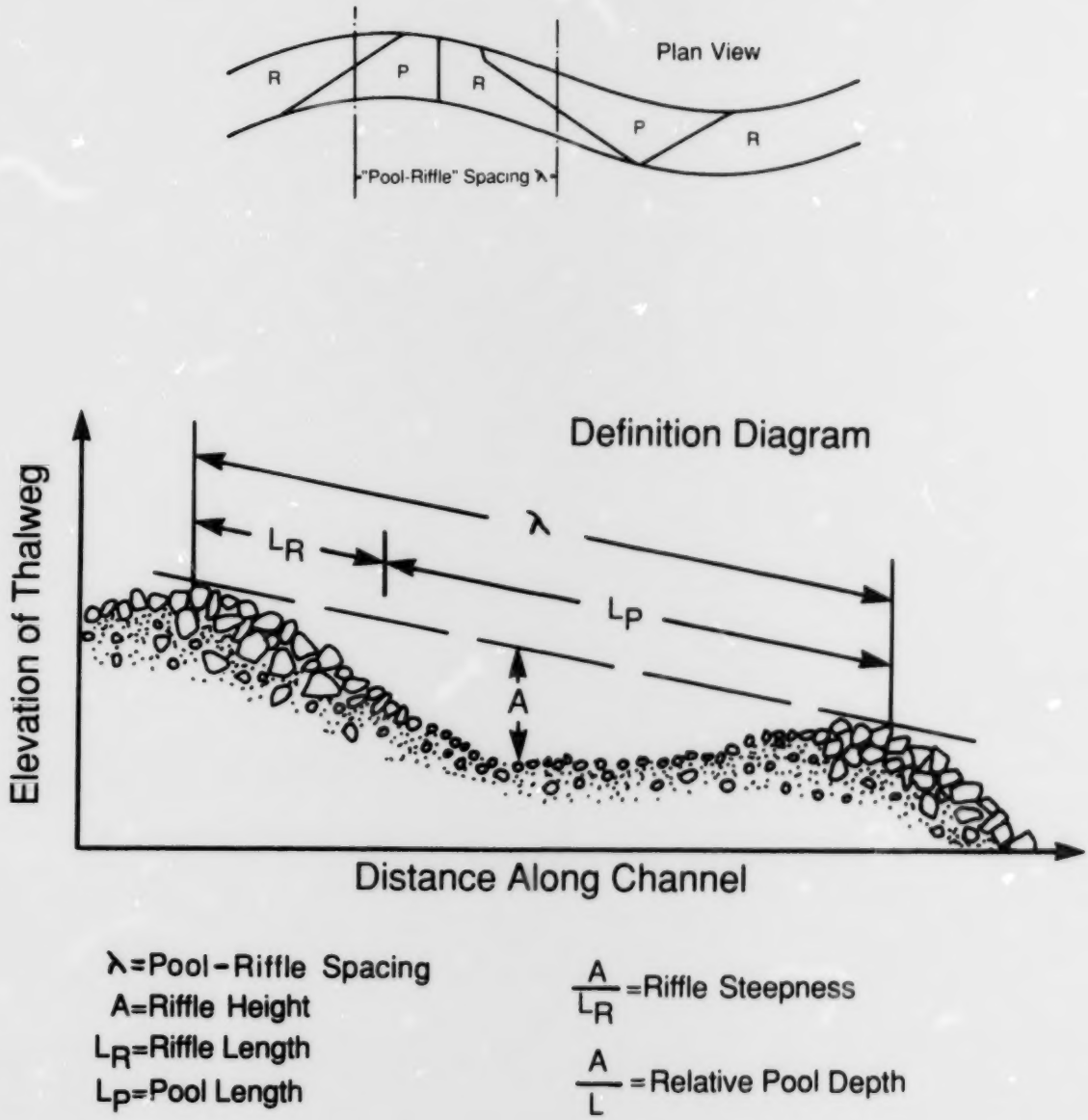

FIGURE 2. Schematic of method for determining riffle spacing, height, steepness, and pool depth (from Hogan 1986).

and their areal extent was digitized. The mean depth of deposit was obtained from the cross-sectional transect plots, and are relative to a streamflow stage of zero discharge. This was based on the elevation of the downstream pool-riffle break.

Sediment characteristics

The textural size distributions of surface sediment were determined qualitatively. Estimates of sediment sorting, areal distribution, and stability were obtained from the low-level air photographs and field notes. Sediment storage characteristics were assessed by the methods described above.

3.2.2 Fish and fish habitat surveys

The format of surveying juvenile rearing habitat followed that used during the 1983/84 synoptic surveys by FFIP (Tripp and Poulin 1986a). Each pool, glide, and riffle in the study sections was described and measured separately. The material or feature (e.g., streambed, streambanks, LOD, boulders) controlling the nature of each habitat unit was recorded, along with the average length and width of the feature. Fish cover (e.g., LOD, small organic debris, overhanging vegetation, turbulence, boulders, and deep water) was similarly identified and measured.

Habitat values were tabulated on computer spreadsheet software and analyzed. Parameter values were summarized and expressed as a percentage of surface area of the stream sections involved.

Juvenile salmonids were enumerated in the study reaches to determine the effect of LOD site construction on standing fish crops. Population estimates were made for each stream feature in Macmillan, Sachs, and Bonanza tributary creeks. A mark recapture technique (Bailey 1951) was used to calculate population size, except in portions of Bonanza tributary where numbers were too low. There a two-pass method (Seber and LeCren 1967) or a three-pass method (Zippin 1956, 1958) was used.

For the multiple pass estimates, the 95% confidence limits were calculated by:

$$\text{confidence limit} = N \pm 1.96 \sqrt{[n_1^2 \times n_2^2 (n_1 + n_2) + (n_1 - n_2)^4]}$$

where n_1 = number of fish captured in the first pass and

n_2 = number of fish captured in the second pass

For the mark recapture estimates, the 95% confidence limits were calculated by:

$$\text{confidence limit} = N \pm 1.96 \sqrt{[M^2 (C + 1) (C - R)] + [(R + 1)^2 (R + 2)]}$$

where M = number of fish marked in the first pass

C = number of fish caught in the second pass

R = number of previously marked fish recaptured in the second pass

Fish were largely caught by electroshocking, with pole seining augmenting samples in pool areas.[2] Marked fish were released for more than 6 hours before recaptures began. Fish numbers from stream features of the less densely populated Southbay Dump Creek were combined within the upper study reach and with those within the lower control reach to generate statistically significant sample sizes. For the post-winter population estimates, two to three Gee minnow traps baited with roe were set overnight at each site. No effort was made to isolate the sites.

3.2.3 Gravel analysis

Intragravel Dissolved Oxygen (DO), intragravel permeability, and gravel composition were measured at each of the 20 planned LOD placement sites, the two gabion sites, and their controls. Sample procedures were similar to those in previous FFIP studies (Tripp and Poulin 1986b), and included the use of a 500-mL stainless steel syringe and Hach DO kit, a Terhune Mark VI permeability standpipe (Terhune 1958), and a modified McNeil gravel sampler, respectively. Data were collected on gravel texture and gravel quality before and 1 year after placement of log structures in the three study streams. On Sachs Creek, where structures were installed in pairs, gravel was investigated upstream, between, and downstream of each setting. On Macmillan and Southbay Dump creeks, gravel was investigated upstream and downstream from individual structures or structure groupings. In Sachs Creek, gravel was sampled at five positions across the channel on each sample line, and in the other streams at three sample positions.

Gravel texture analyses from the McNeil samples encounter problems of representation for the largest material sizes. Hence, size distributions and textural parameters were calculated from <25.4-mm fraction only. Parameters for analysis were as follows:

- median size of gravel (D_{50})
- mean size of gravel (D)
- proportion finer than 3.36 mm
- proportion finer than 0.85 mm
- Fredle index
- permeability
- dissolved oxygen of interstitial water

3.2.4 Engineering assessment

The LOD structures were viewed from an engineering perspective with respect to low flow and flood stream hydraulics, sediment transport, and structural integrity. Anticipated local flow

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[2] Tripp, D.B. and V.A. Poulin 1989. The effects of logging and mass wasting on salmonid juveniles in Queen Charlotte Islands streams. B.C. Min. For. In prep.

characteristics guided the placement of the logs; and the need for permanent scour pools and stable geomorphic features were considered together with an overall stabilization of the stream channel. The use of deadmen anchors and the brace log on the arch structures, as well as the pre-excavation of scour holes and loading of sediment storage areas, were part of the engineering assessment. The areas of sediment loading were against the log emplacements adjacent to the banks, well away from gravel sampling areas within the channel.

3.3 Site Construction

3.3.1 Log placements

The LOD placement and pool configurations were individually tailored to each site, and took into account structure stability, the desired habitat, and maintenance of fish passage. Variations of two basic LOD configurations were used. These included horizontally diagonal cross-stream obstructions pointing upstream (Figure 3; Plate 1) and arch-like structures having apices directed upstream (Figure 4; Plate 2).

Logs selected for the designated LOD structures were skidded to the rehabilitation sites with a tracked excavator or a rubber-tired skidder. To avoid damaging in-stream habitats, care was taken to restrict all activity except log placement to off-channel portions of the flood plain. The excavator placed the logs in pre-determined positions, aligning them vertically by alternately digging or filling trenches to achieve the desired attitude. The LOD structures were anchored securely with discarded logging cable so that they would maintain position during stormflows. At several sites, anchorage required structures to be cabled tightly to "deadmen" buried into the substrate. Approximately 2 x 0.4 m diameter pieces of LOD were used and buried to a depth of approximately 2 m. The deadmen were also placed at the apices of each log arch structure to prevent the structures from floating during floods. At other sites, portions of LOD structures themselves were buried in trenches or cabled to stumps or trees in overbank areas to secure their positions. Where appropriate, the streambanks were riprapped to prevent lateral bank erosion during floods. Modifications made to the sites ensured habitat would be created in the event that floods did not occur before final 1-year post-construction evaluation. These modifications mimicked what was anticipated to occur at the sites from a geomorphological perspective. To this end, appropriate areas were excavated to form scour pools and anticipated sediment storage areas were pre-filled.

3.3.2 Off-channel pools

Individual off-channel pools (Plate 3; Appendix 3) were constructed by blasting and placed in multiples to form a "beaded channel." The purchase, preparation, and detonation of explosives for the pond development study was contracted to a licensed blaster. Quantities of Amax (the primary explosive) and dynamite (the detonator) were buried into the substrate at designated locations to create beaded channels.

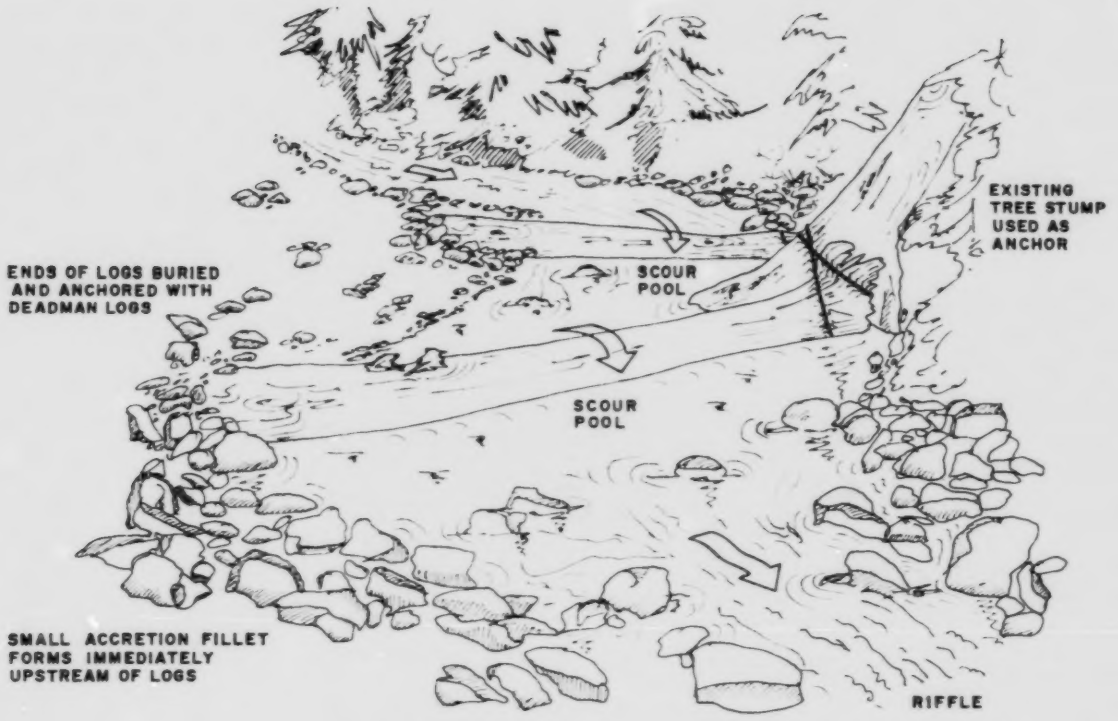


FIGURE 3. Oblique diagram of tandem single log emplacement.

PLATE 1. Single log emplacements.

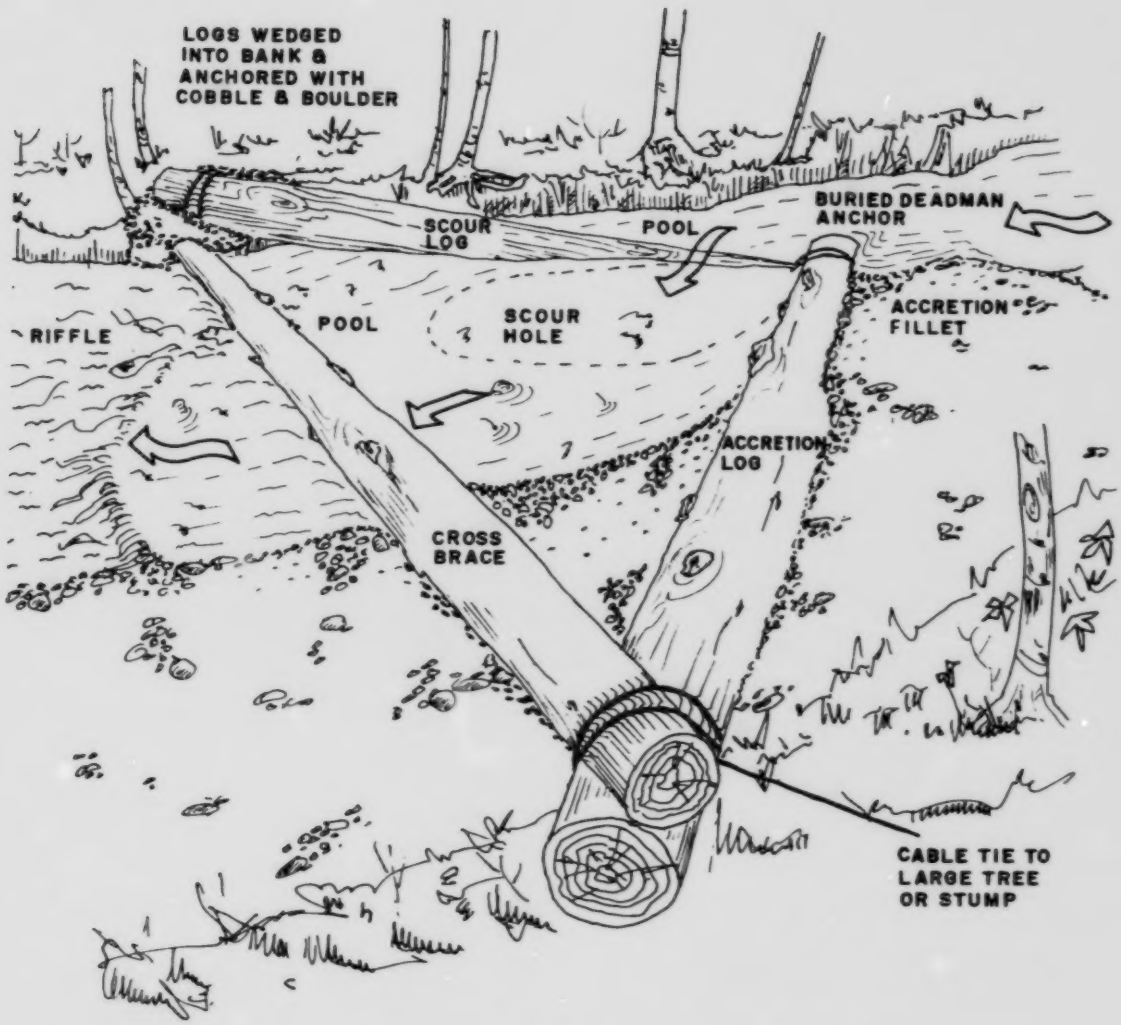


FIGURE 4. Oblique diagram of multiple-log arch emplacement.

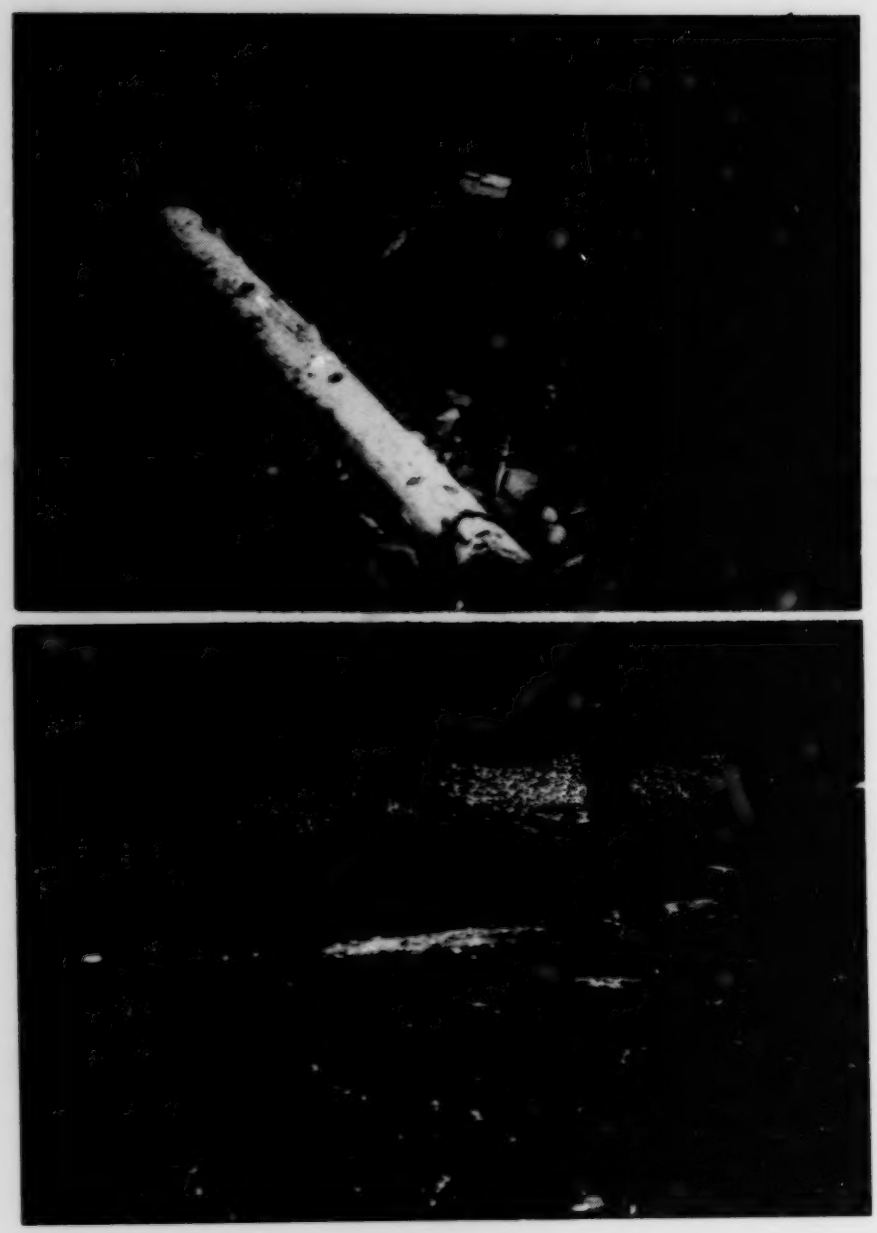


PLATE 2. Multiple-log arch emplacements.

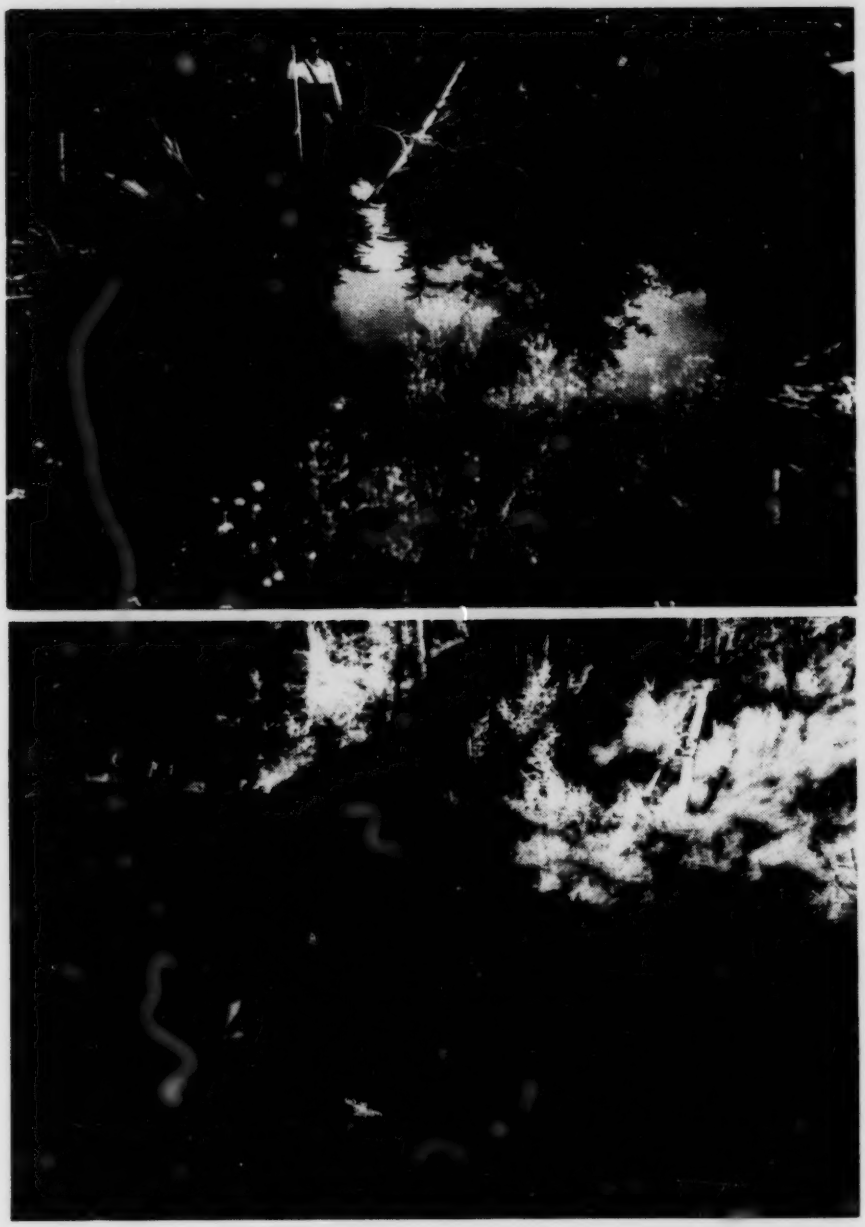


PLATE 3. Blast ponds.

3.4 Construction Monitoring

Measurements were made during the construction phase to document the impact of construction activities on water quality. Depth-integrated water samples were taken during site construction for suspended sediment determination. Samples were taken at varying distances downstream of active site construction on Sachs, Macmillan, and Southbay Dump creeks. Samples were preserved and later analyzed for total suspended solids at Chemex Labs Ltd. in North Vancouver.

Sediment traps were also used to measure accumulated suspended sediment deposition on Sachs and Macmillan creeks. Aluminum pie plates (20 cm diam.) were filled with sorted beach pebbles ranging in size from 6.3 -12.5 mm and inserted flush with the streambed in replicates of three at pool and riffle sites, at varying distances downstream of site construction. After construction was completed, the samples were carefully removed from the streambed, drained of excess clear water, and dried. Deposited sediment was separated from the sorted pea gravel by mechanical agitation of sieves and collection of material passing through a 1.18-mm sieve. Values obtained at test sites were standardized against values obtained at control sites upstream of construction

Materials, costs, manpower, and timing required during the construction phase were itemized for all sites.

3.5 Post-Construction Cleanup

Stream rehabilitation sites were cleaned after construction. Small organic debris introduced to the stream channel during construction was removed and gravel berms from excavator tracks were levelled. Freshly exposed soil where streambanks and gravel bars were scarred was manually seeded with a grass-legume mix, and fertilized to accelerate revegetative processes. Side channels were manually cleared to provide fish access to the pond developments. Finally, cables were tightened at the LOD placement sites to ensure that the positions of the structures would not shift during floods.

3.6 Post-Construction Evaluation

Many of the pre-construction site analyses were repeated soon after construction and again 1 year later at Macmillan, Southbay Dump, and Sachs creeks. In-channel topography of the study reaches was re-surveyed. Positions, inclinations, and sizes of the LOD placements were measured. Cross-sections established before construction were re-surveyed. Low-level aerial photography was conducted at the study reaches to aid in re-mapping the study sites. Habitat surveys were repeated in the study reaches to detect changes brought on by site construction. Juvenile surveys were repeated in the LOD study reaches 1.5 months and 1 year after construction so that any shifts in fish utilization at the rehabilitation sites could be detected. Streambed parameter measurements of intragravel permeability and DO concentration were repeated at LOD sites 1 year after construction as well.

Gravel scour monitors buried vertically in the stream gravel (Tripp and Poulin 1986b) were installed and monitored at LOD study sites to determine the depth of gravel scour during the first season of floods. An engineering/geomorphic evaluation of the LOD placements was provided by Hay & Company Consultants Inc.

4 RESULTS AND DISCUSSION

4.1. Channel Morphology

4.1.1 Longitudinal profiles

Longitudinal channel changes within reaches with log placements (treatment reaches) and without log placements (control reaches) are shown as an overview in Figures 5, 6, and 7. These graphs indicate scour and deposition along the thalweg over the course of 1 year. Changes along the channel edges are considered in Section 4.1.2.

Generally, the long profiles show distinct pool-riffle sequences and larger, more extensive, sediment bars. The former are evident throughout the reaches and these are superimposed on the larger lobes, as seen upstream of the 320 m point in Southbay Dump (Figure 10). Visual inspection of the long profiles indicates that there are more frequent, and larger, pools in the treatment reaches, compared to the control sites. This increase in pool extent is evident in each treatment site in all reaches. There are also cases where pool-riffle sequences have changed over the year in the control sites. Therefore, although there is more pool length in the treatment sections due to log placement, there have also been changes in control sites. These appear also to be due to naturally occurring debris pieces.

Other than visual inspection of the longitudinal profiles, it is often difficult to compare them quantitatively because the distances along the thalweg usually change with repeat surveys. For example, if a debris piece shifts from parallel to perpendicular in the channel, so that a pool is scoured laterally across the bed where no pool existed previously, the thalweg profile would follow the lateral pool. This results in longer profile lengths even though the overall reach length is not altered. When repeat surveys are compared, those shifts should not be confused with apparent scour or deposition.

In an attempt to quantify the longitudinal profiles, an analysis of depth variability was undertaken (the method used is discussed in Section 3.2.1). This procedure is not influenced by variable thalweg lengths. Results of these analyses are given in Table 2. The individual reaches show several instances where the depth variability actually decreased over the 1-year period in the control. In most cases, with minor exceptions in the lowest reach of Macmillan Creek (logs placed above the channel bed) and Southbay Dump Creek, an increase in depth variability was documented over the year period in the treatment reaches. This general pattern of increased depth variability resulting from log structures is also shown in the averaged standard error (deviation) values presented in Table 2.

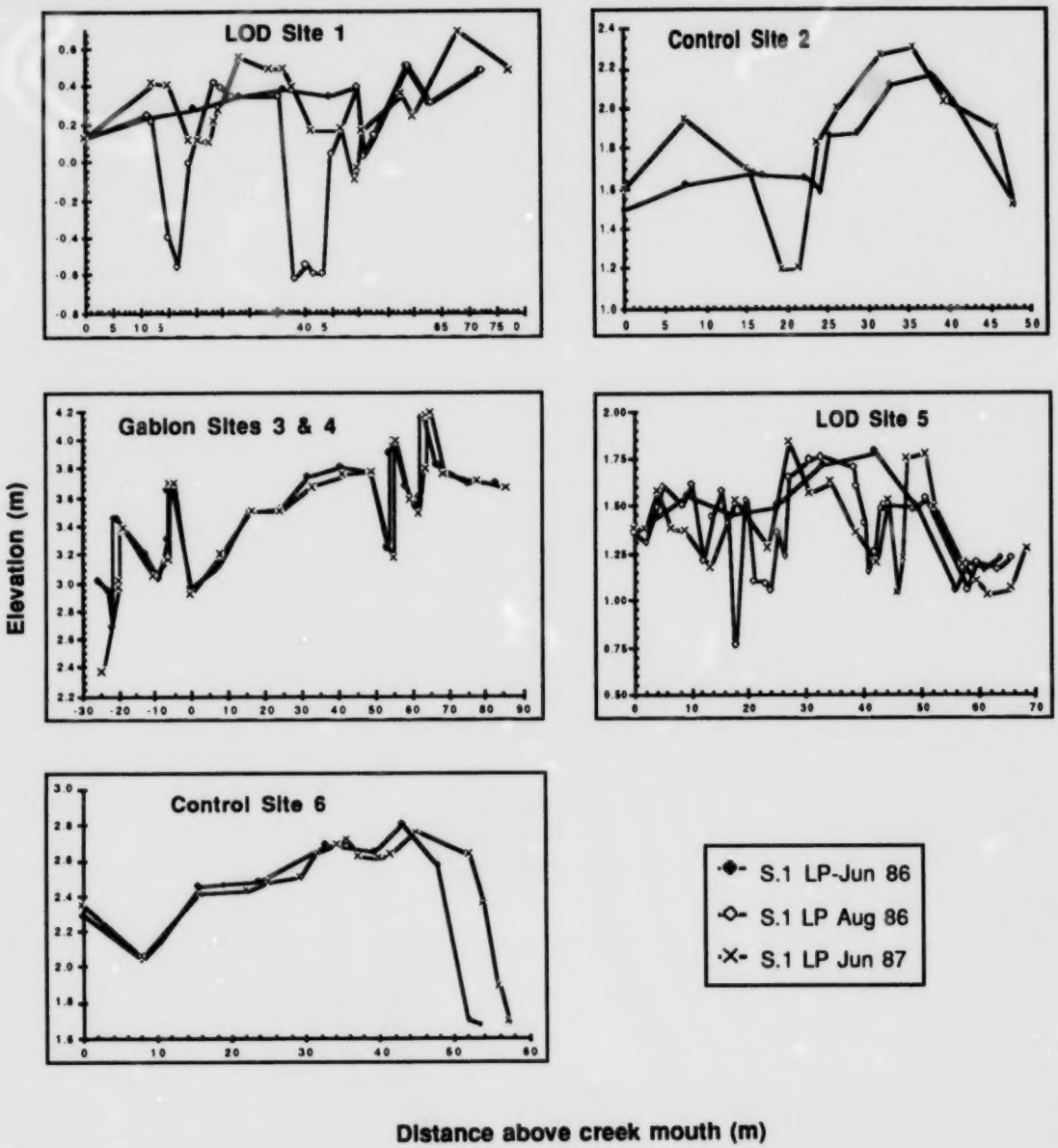


FIGURE 5. Longitudinal channel changes showing scour and deposition along the thalweg at Sachs Creek.

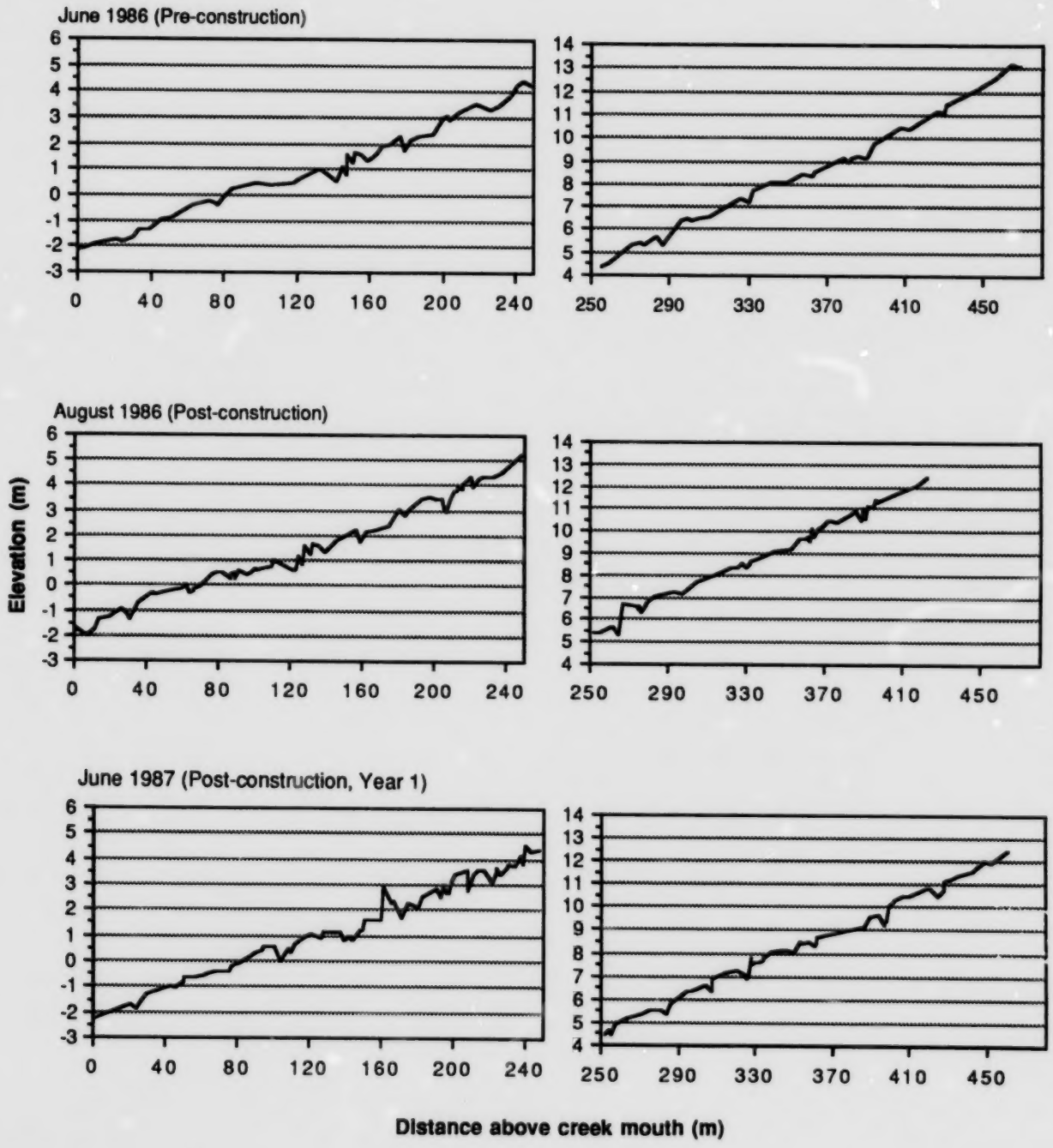


FIGURE 6. Longitudinal channel changes showing scour and deposition along the thalweg at Macmillan Creek.

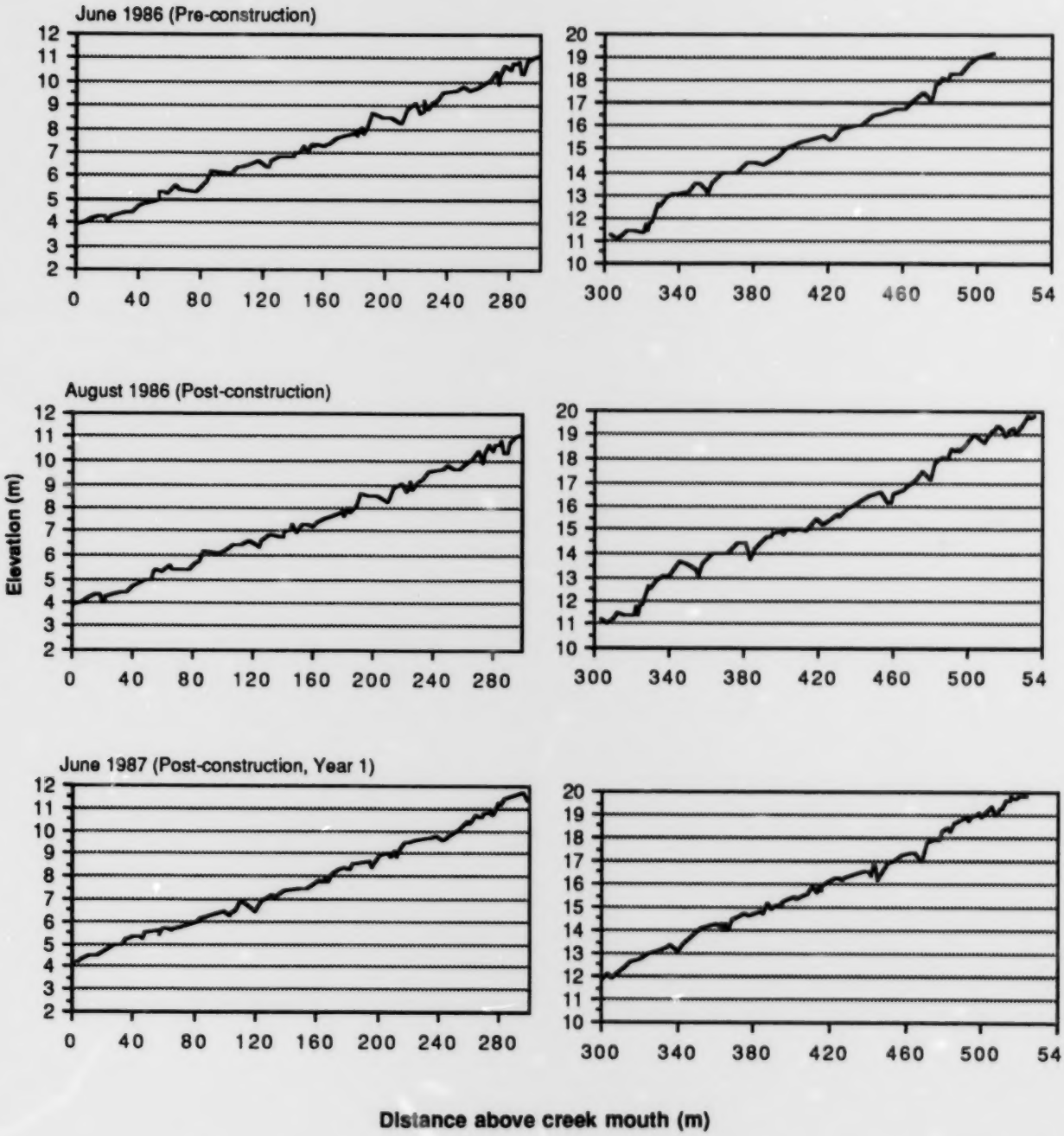


FIGURE 7. Longitudinal channel changes showing scour and deposition along the thalweg at Southbay Dump Creek.

TABLE 2. Depth variability at study sites in Sachs, Macmillan, and Southbay Dump creeks

Stream and site[a]	Reach Type	Gradient (m/m)	Standard error (SE) June 1986	June 1987	% Change (100x[SE87-SE86]/SE87)
Sachs 1	Treatment	0.0025	0.138	0.205	32.6
Sachs 2	Control	0.0080	0.203	0.364	44.2
Sachs 3&4	Gabion	0.0075	0.273	0.304	10.2
Sachs 5	Treatment	0.0040	0.215	0.231	6.9
Sachs 6	Control	0.0100	0.386	0.310	-24.5
Mc 1	Treatment	0.0255	0.169	0.168	-0.6
Mc 2	Control	0.0300	0.253	0.377	32.9
Mc3	Treatment	0.0280	0.210	0.249	15.7
Mc4	Control	0.0395	0.215	0.183	-17.5
Mc 5	Treatment	0.0350	0.162	0.200	19.0
Mc 6	Control	0.0420	0.097	0.145	33.1
Mc 7	Treatment	0.0480	0.177	0.296	40.2
Mc 8	Control	0.0495	0.145	0.116	-25.0
SBD	Treatment	0.0355	0.240	0.239	-0.4
SBD	Control	0.0230	0.172	0.161	-6.8
Summary averages			SE		
			1986	1987	% Change
Sachs	Treatment		0.177	0.218	19
Sachs	Control		0.295	0.337	13
Sachs	Gabion		0.273	0.304	10
Mc	Treatment		0.180	0.228	21
Mc	Control		0.178	0.205	13
SBD	Treatment		0.24	0.239	-0.4
SBD	Control		0.172	0.161	-7

[a] Where Sachs = Sachs Creek, Mc = Macmillan Creek, SBD = Southbay Dump Creek.

4.1.2 In-Channel topography and bed configurations

Plan view maps of the LOD placement sites and resultant changes in channel morphology are illustrated in Figures 8, 9, and 10. These maps show the morphological setting in pools, riffles, and bars before construction, immediately following construction and 1 year after construction. Habitat implications are discussed in Section 4.3 of this report. The channel gradients for each reach are given in Table 2.

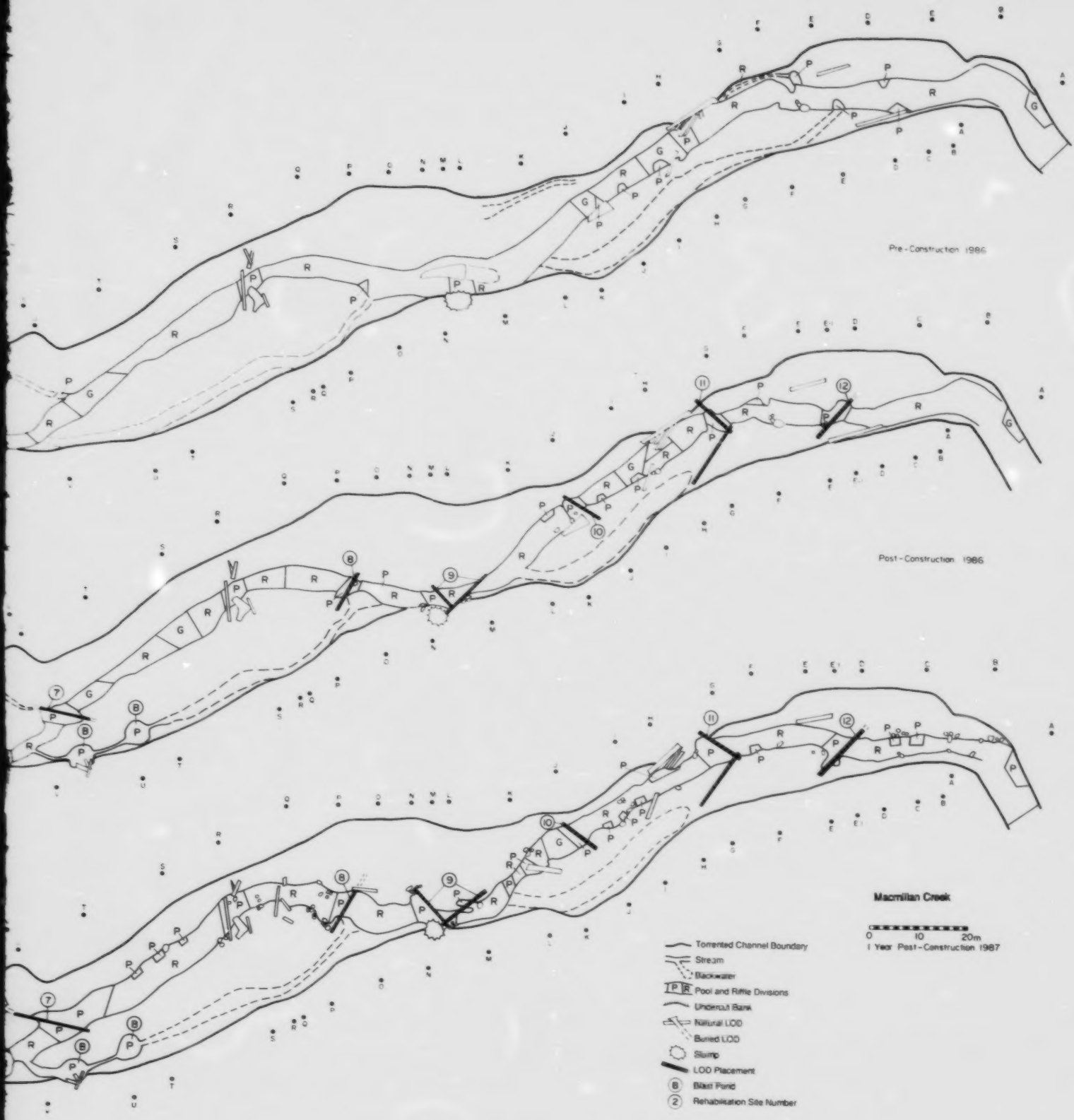
In 1986, before log placement, all stream reaches had minimal quantities of LOD present in-channel compared to other local streams (Hogan 1986; Tripp and Poulin, 1986a). Further, as discussed earlier, the arrangement of this material produced specific channel features. The general absence of debris, and its predominant parallel orientation, resulted in poor channel diversity as characterized by uniform width, minor bank-cutting, and uniformity in sediment texture. The importance of debris budget and its impact on channel morphology is discussed in detail in Hogan (1987). Conditions in Southbay Dump Creek before log placement are also evaluated in Hogan (1987) and pool-riffle characteristics in Sachs Creek are considered in Hogan (1985).

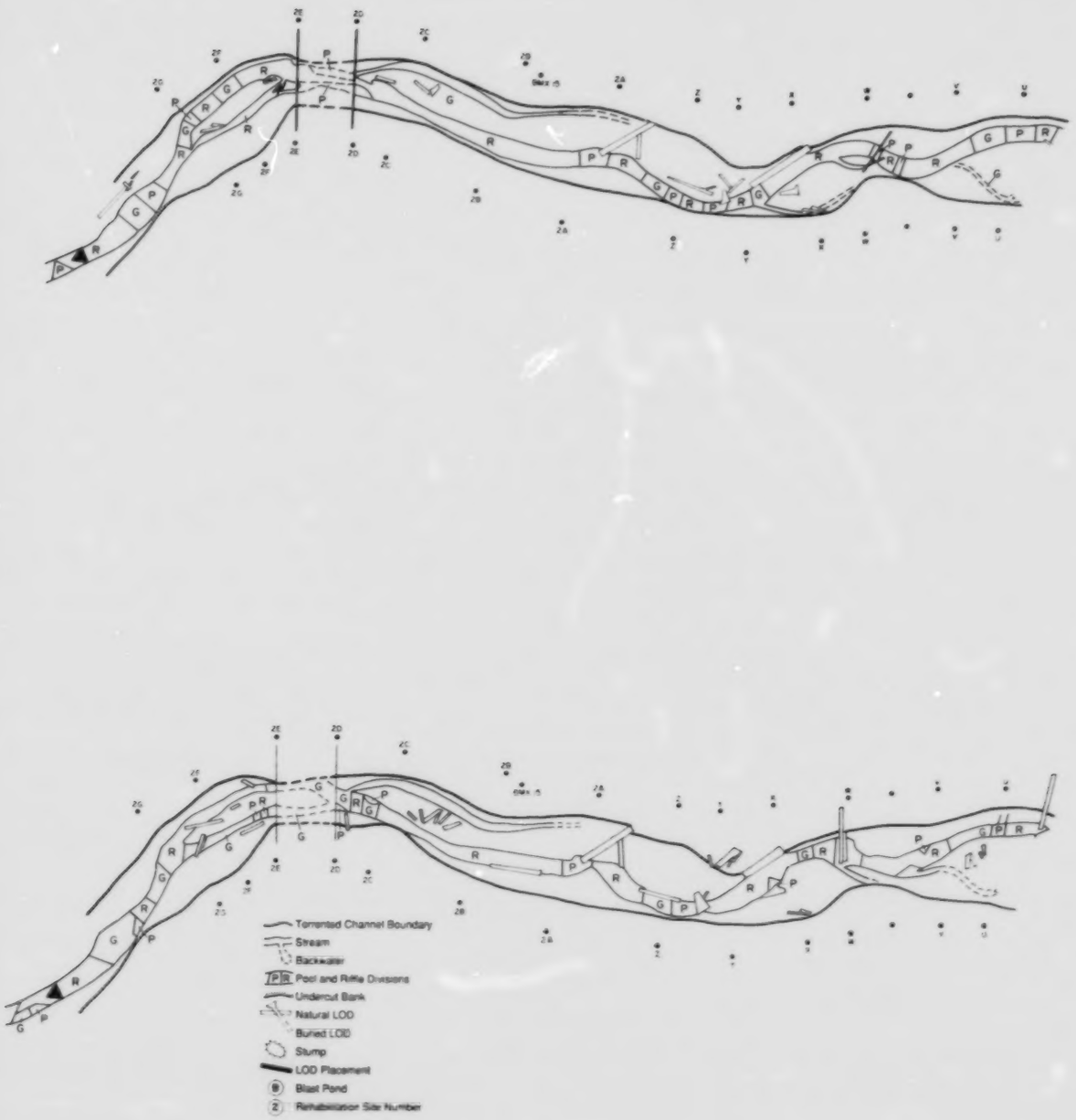
After log placement, pool and riffle configurations were altered. As seen in Figures 8, 9, and 10, pools are more frequent and the proximal riffles smaller. Pool shapes reflect the orientation of the placed debris. In those cases where the debris piece was located in the correct vertical position, or was angled down into the bed, a plunge pool was scoured on the downstream side of the debris and sediment was stored on the upstream side of the debris piece. Several examples are seen in Figures 8 (Macmillan Site 12) and 10 (Sachs Site 5). At those sites where the debris was located too high and the channel was degrading over the year, a lateral scour pool developed along the log, and sediment was scoured from upstream of the log and deposited downstream (e.g., Figure 9, Southbay Dump Creek Site 2). If the log placement was sufficiently high, as in Site 3 (Figure 8), it had no influence on water or sediment transfer and did not change the channel bed.

One of the main characteristics of LOD, besides its influence on pool and riffle development, is its sediment stabilizing capabilities (Lisle 1986; Hogan 1987). In the present study, this aspect has been considered in two ways because sediment is stored along the channel in two distinct ways. As shown in Figures 6, 7, and 8, there are large depositional sections and smaller zones associated with individual debris pieces, channel beds, or, in some cases, bedrock outcroppings.

The cross-sections were analyzed to document larger scale channel changes over the 1-year period. Figures 11, 12, and 13 show zones of net aggradation (building) and degradation (eroding). The methods used to construct these graphs are given in Section 3.2.1.

FIGURE 8. Plan view maps of morphological settings of study reaches at Macmillan Creek showing LOD placement strategy and pre-construction, post-construction and 1 year post-construction channel morphology. Hubs for cross sections are listed alphabetically.


Pre-Construction 1986
Post-Construction 1986
Macmillan Creek
0 10 20m
1 Year Post-Construction 1987
Tormented Channel Boundary
Stream
Backwater
Pool and Riffle Divisions
Undercut Bank
Natural LOD
Buried LOD
Slump
LOD Placement
Blast Pond
Rehabilitation Site Number



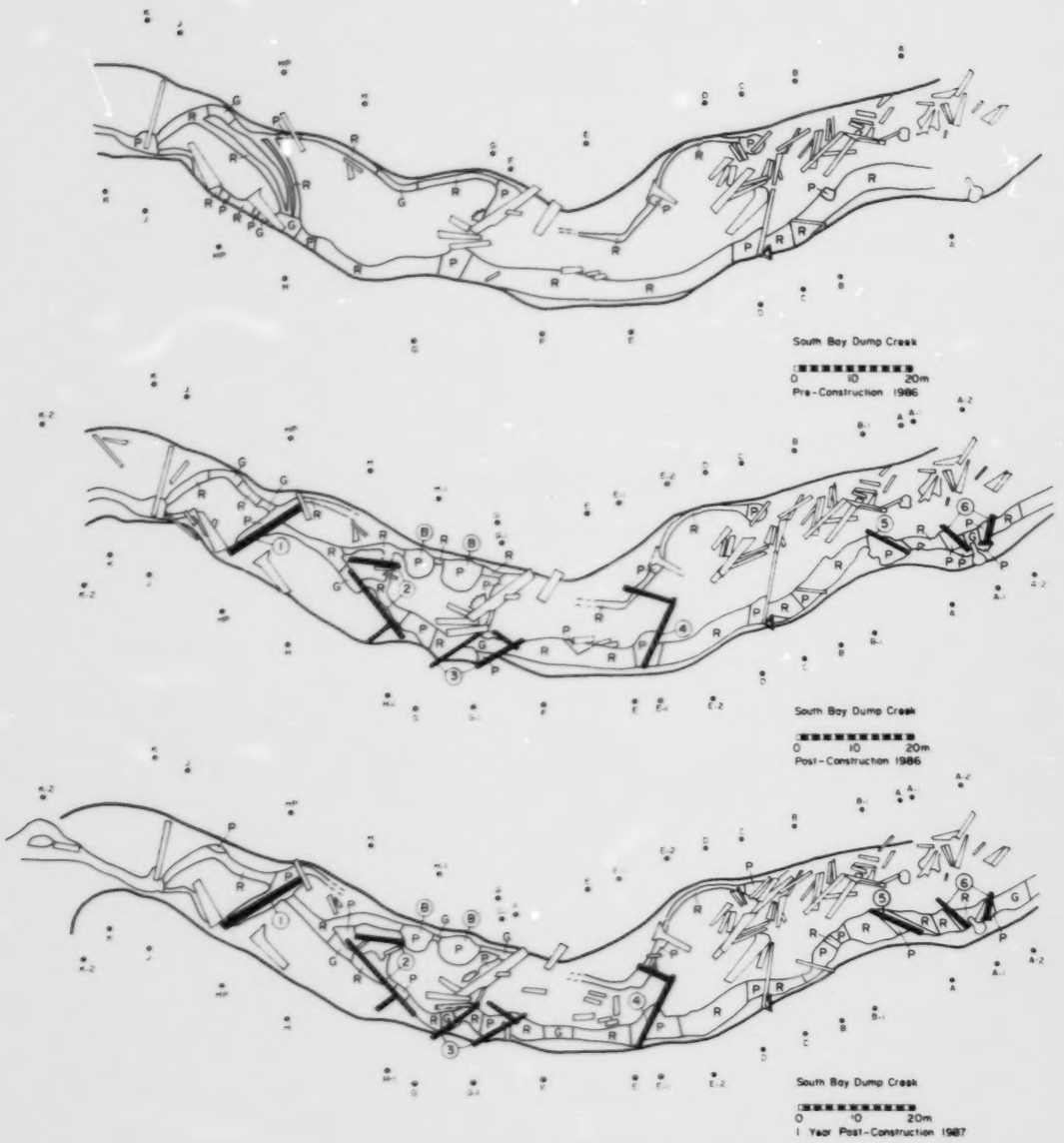


FIGURE 9. Plan view maps of morphological settings of study reaches at Southbay Dump Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Hubs for cross-sections are listed alphabetically.

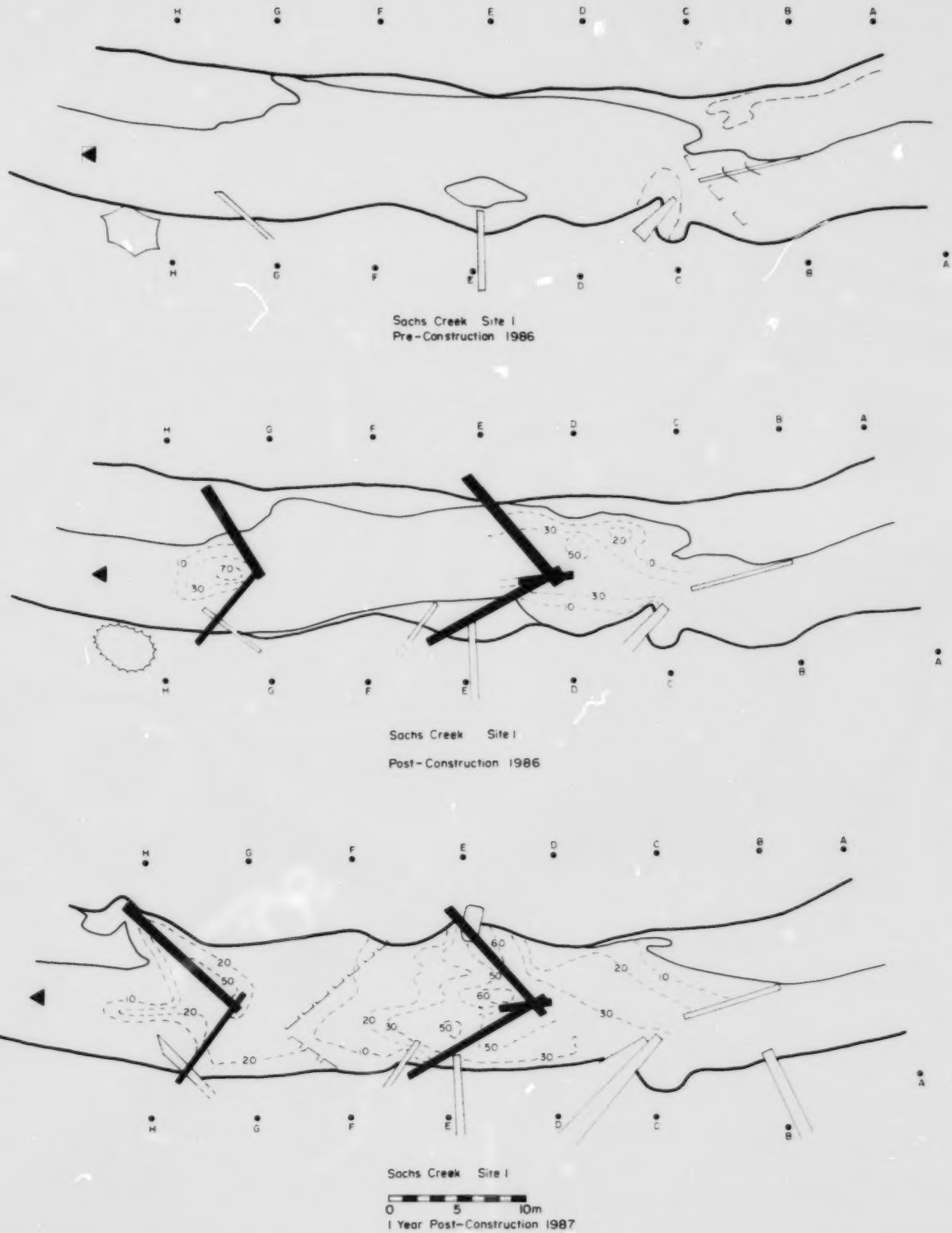


FIGURE 10a. Plan view maps of morphological settings of study reaches at Sachs Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Low flow depth contours are expressed in centimetres. Hubs for cross-sections are listed alphabetically.

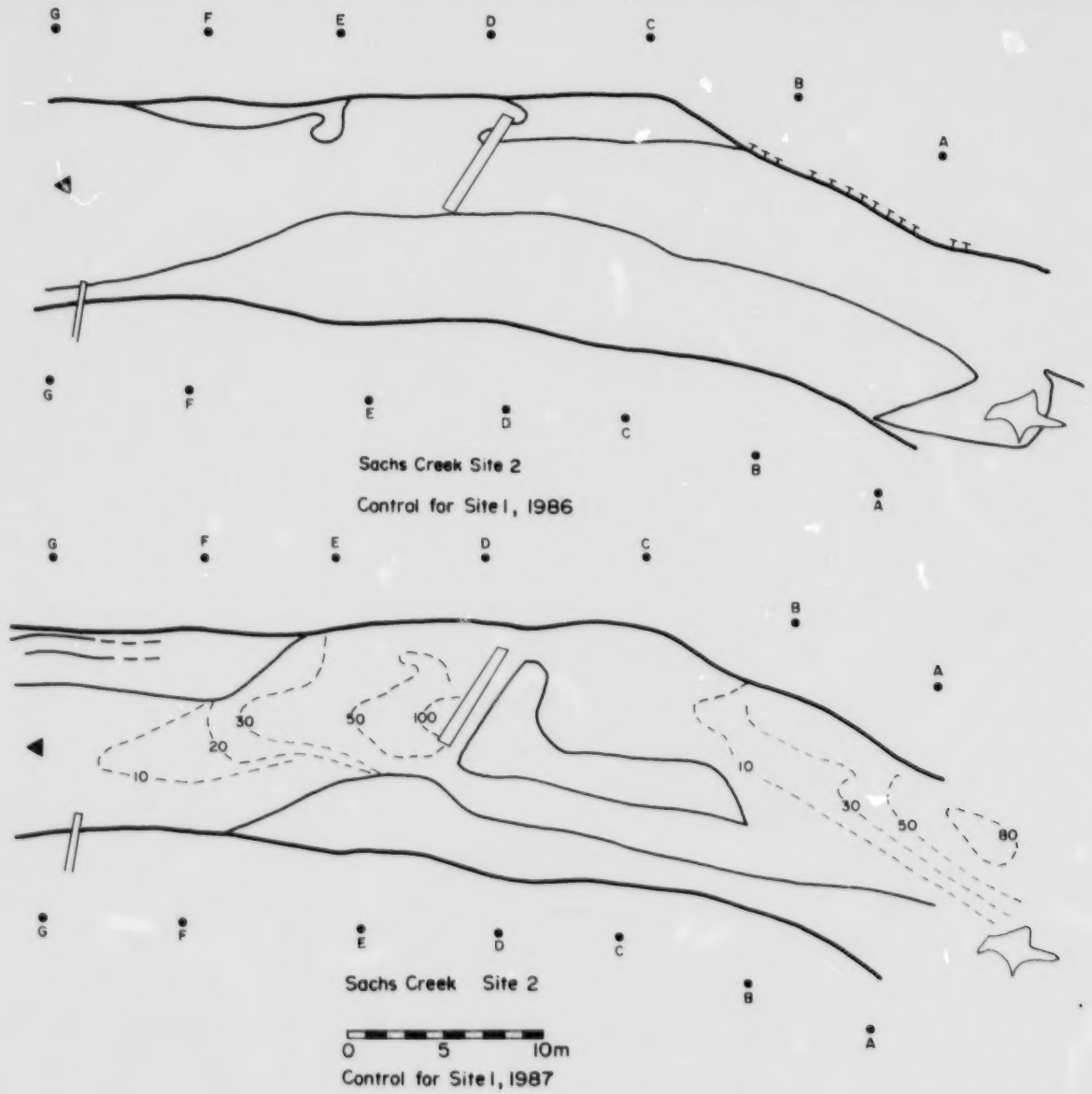


FIGURE 10b. Plan view maps of morphological settings of study reaches at Sachs Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Low flow depth contours are expressed in centimetres. Hubs for cross-sections are listed alphabetically.

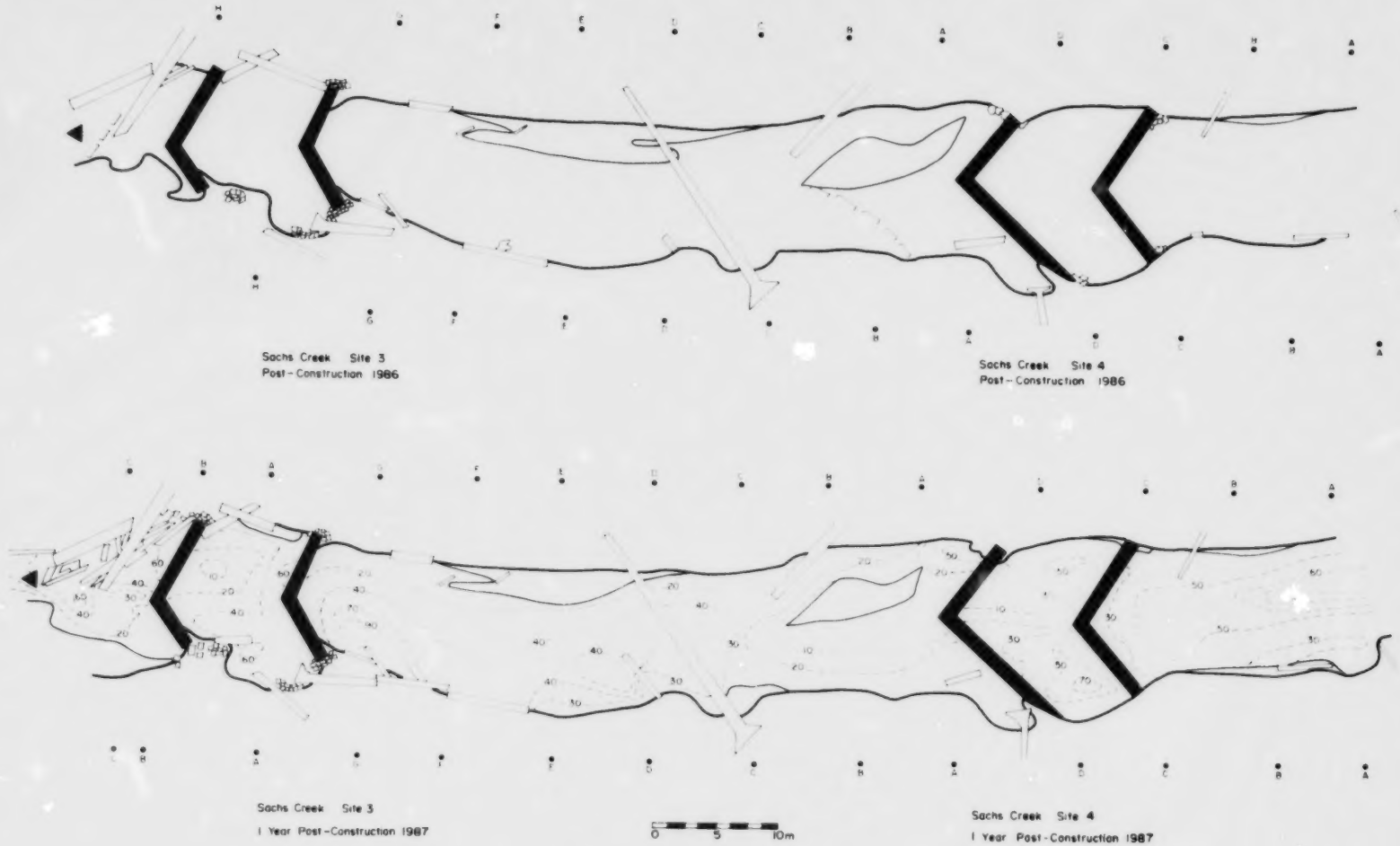


FIGURE 10c. Plan view maps of morphological settings of study reaches at Sachs Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Low flow depth contours are expressed in centimetres. Hubs for cross-sections are listed alphabetically.

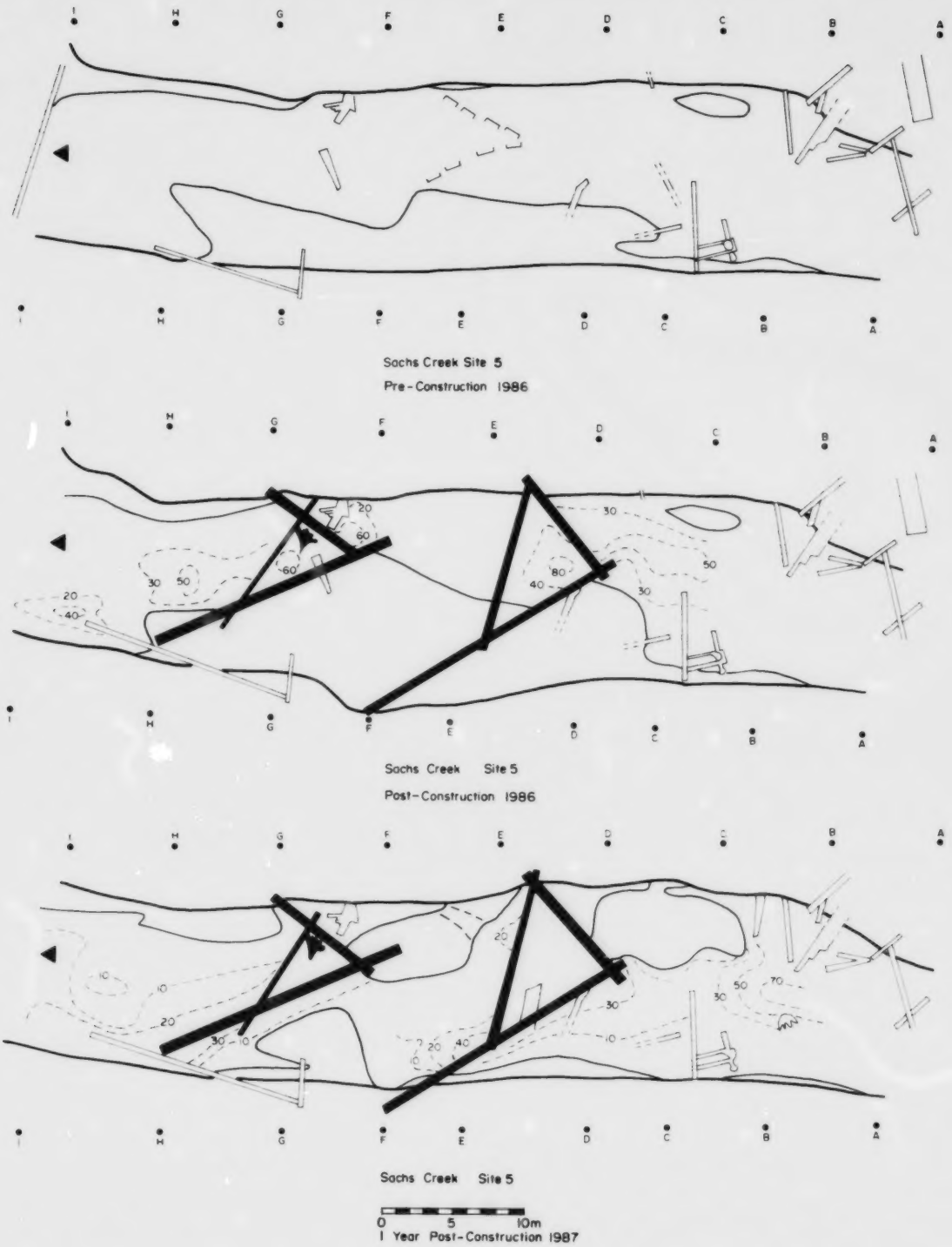
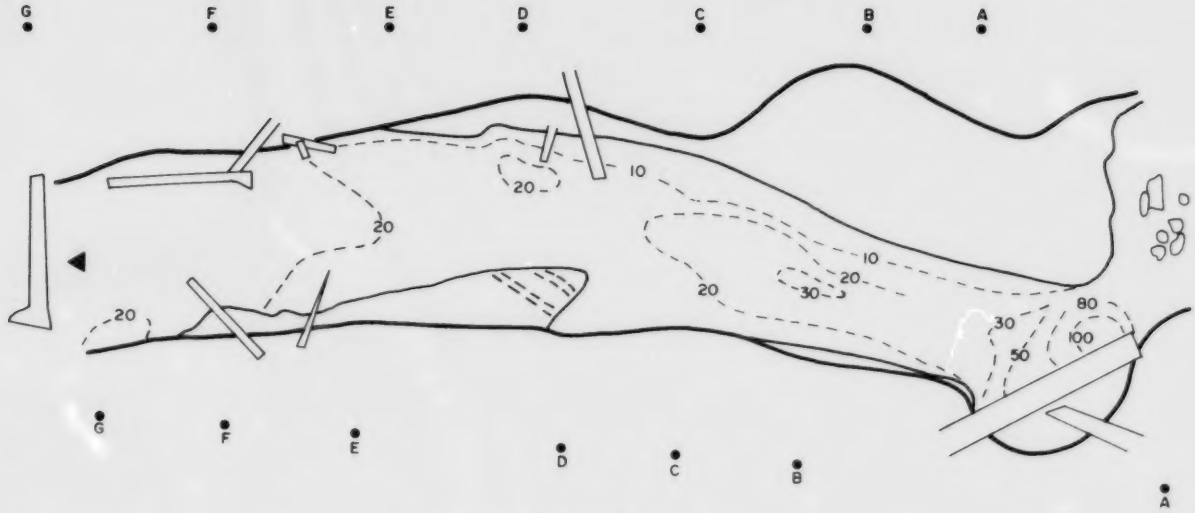
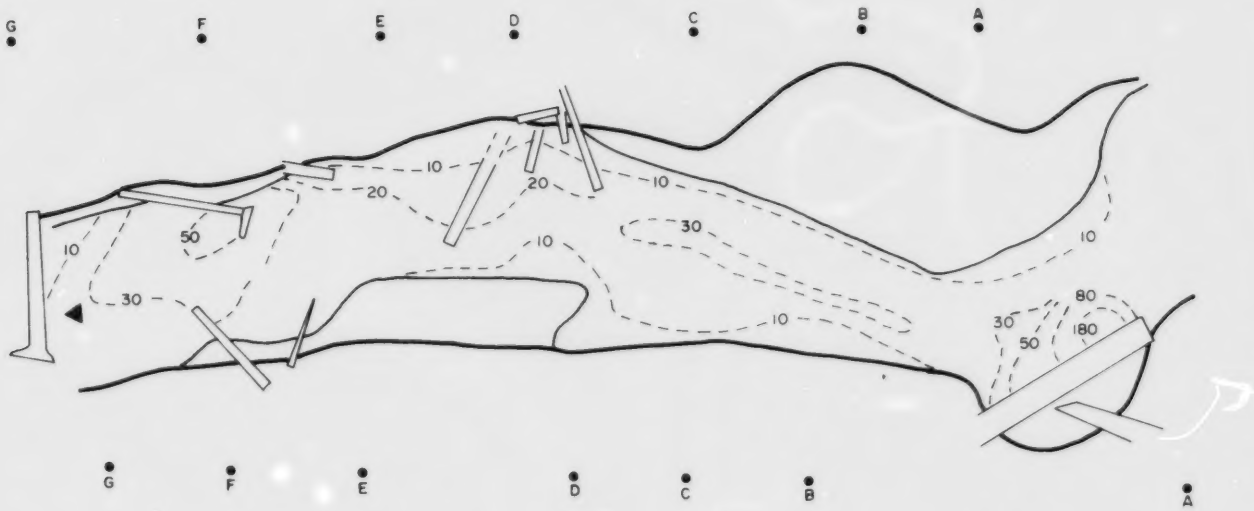


FIGURE 10d. Plan view maps of morphological settings of study reaches at Sachs Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Low flow depth contours are expressed in centimetres. Hubs for cross-sections are listed alphabetically.



Sachs Creek Site 6

Control for Site 5, 1986



Sachs Creek Site 6

0 5 10m

Control for Site 5, 1987

FIGURE 10e. Plan view maps of morphological settings of study reaches at Sachs Creek showing LOD placement strategy and pre-construction, post-construction, and 1-year post-construction channel morphology. Low flow depth contours are expressed in centimetres. Hubs for cross-sections are listed alphabetically.

Sachs Creek (Figure 11) shows clearly the importance of larger scale influences. Sites 1 and 2 both experienced net aggradation between 1986 and 1987 while Sites 3 and 4 underwent net downcutting (between the gabions) over this course of time. This was due to the breakup of a major log jam located between Sachs Sites 2 and 3. This log jam stored large quantities of sediment upstream, and upon breakup the local channel gradient was increased, and sediment was mobilized and transported out of the immediate location and moved downstream. This sediment apparently deposited in the lower gradient reaches downstream, including Sites 1 and 2. In this case the influence of placed logs was overwhelmed by upstream factors.

Review of Figures 11, 12, and 13 shows that the zone of net building and downcutting must be identified so that logs can be placed in the correct vertical position. Although these locations may change over time, there is usually morphological evidence to indicate which zones will degrade or aggrade in the longer term. This includes the presence of channel bends, bedrock outcrops, major log jams, and boulders (or sediment not transported under the present flow regime).

The second component of sediment storage involves small, discrete storage compartments. These were analyzed as outlined in Section 3.2.1. Results are presented in Table 3.

TABLE 3. Stored sediment volumes at study sites in Sachs, Macmillan, and Southbay Dump creeks, 1986 and 1987

Stream	1986				1987			
	Total vol. (m^3)	No. of sites (n)	Avg. vol./site (m^3)	Std. dev. (m^3)	Total vol. (m^3)	No. of sites (n)	Avg. vol./site (m^3)	Std. dev. (m^3)
Sachs								
Control	165.2	5	33.03	39.96	126.9	5	25.38	22.28
Treatment	116.4	6	19.40	22.68	103.3	8	12.91	9.95
Gabions	21.6	2	10.81	2.03	19.4	2	9.69	3.62
Macmillan								
Control	20.3	3	6.75	5.20	20.3	3	6.75	5.20
Treatment	13.4	3	4.46	3.15	58.5	13	4.50	5.94
Southbay Dump								
Control	130.0	6	21.67	17.87	131.4	6	21.89	17.74
Treatment	18.4	2	9.19	9.28	23.2	6	3.86	3.72

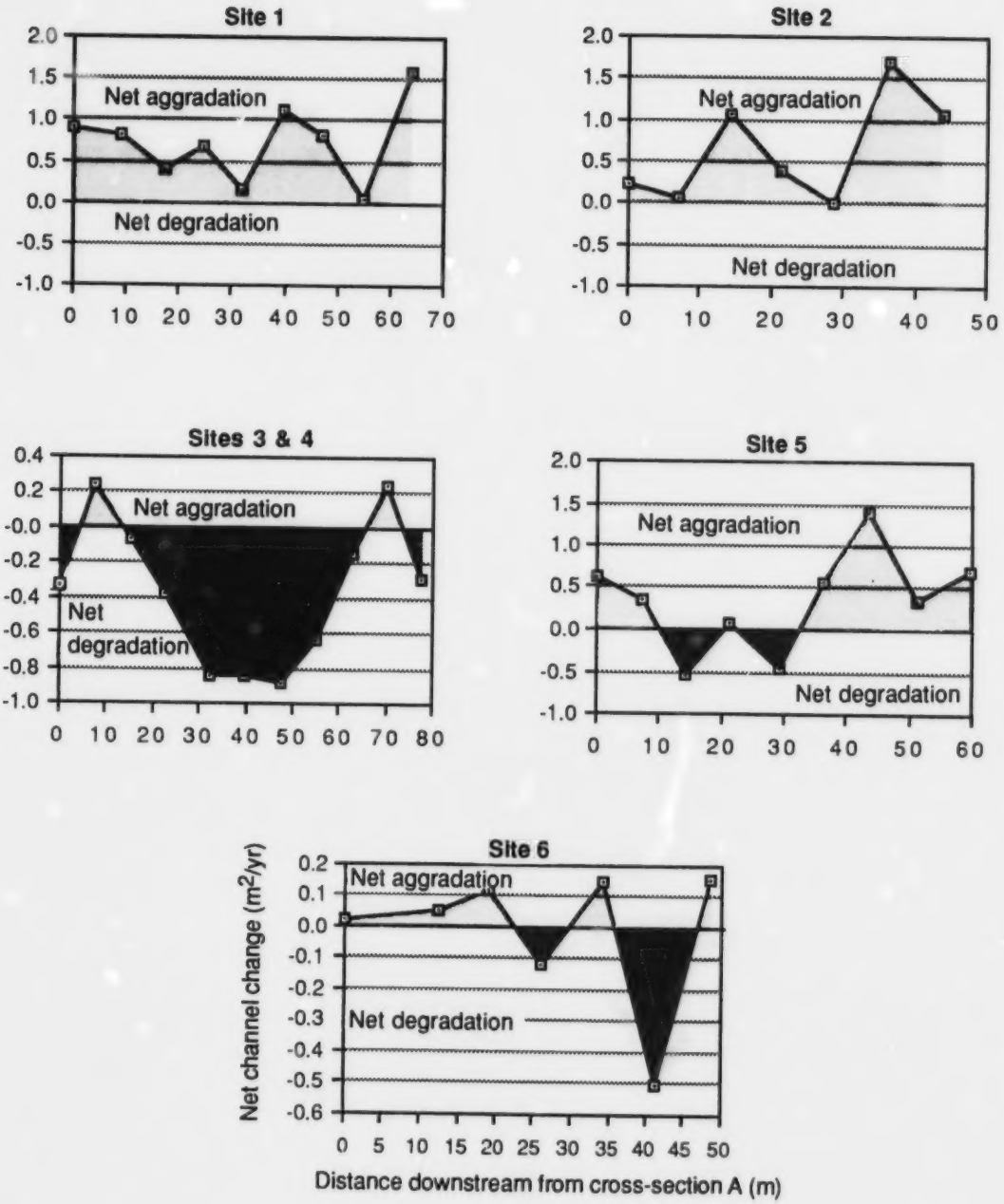


FIGURE 11. Sediment aggradation at study sites in Sachs Creek.

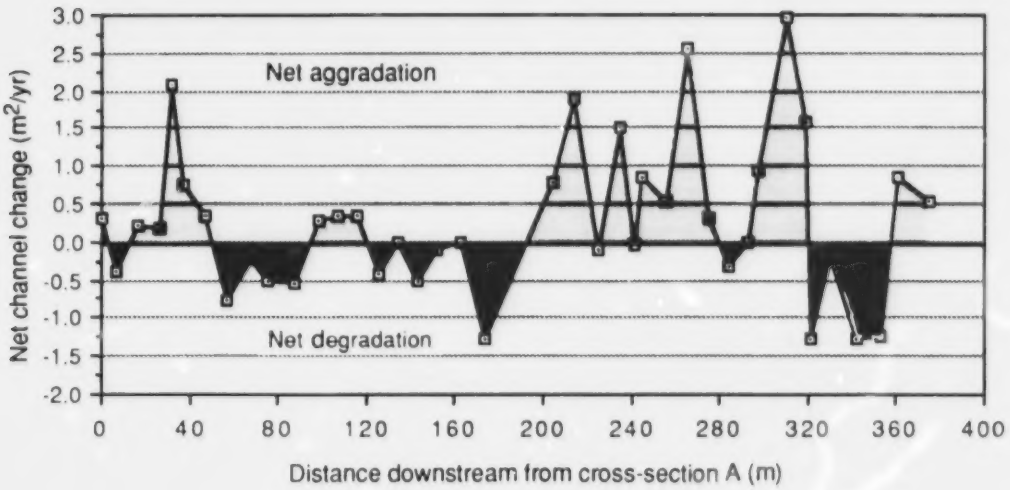


FIGURE 12. Sediment aggradation at study sites in Macmillan Creek.

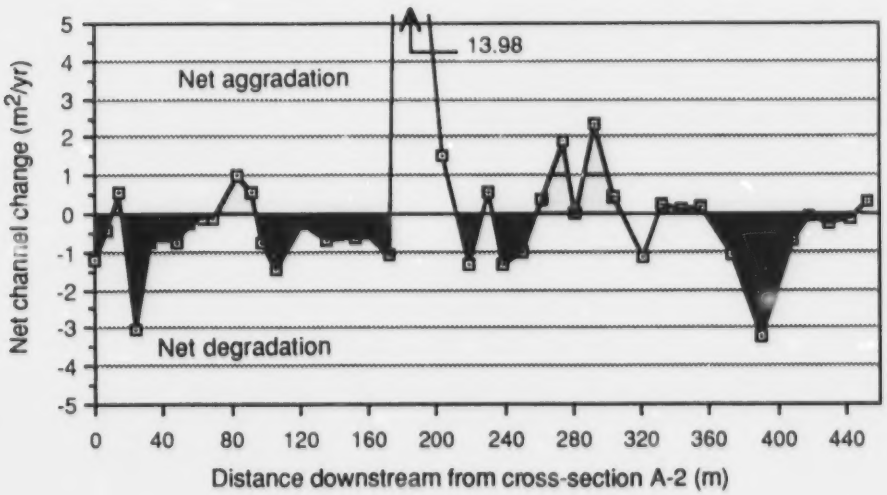


FIGURE 13. Sediment aggradation at study sites in Southbay Dump Creek.

In all study streams the number of storage compartments increased as a result of log placement (Table 3). There was an increase of only 2 sites in Sachs Creek, 4 sites in Southbay Dump Creek, and 10 sites in Macmillan Creek. With the exception of Macmillan Creek, the average size of each compartment was also reduced because of log placement. Hogan (1987) has argued that this increase in log structures frequency and associated decrease in individual storage site size represents an increase in channel stability.

During the 1986-1987 time period in Sachs Creek there was a reduction in side channel bar area which was not related to debris placement. Bars associated with structures were predominantly mid-channel features, with new side channel bars also occurring. Bars in Southbay Dump Creek treatment reaches were usually side channel features and were located on the upstream side of the placed log. The storage sites in Macmillan Creek were more variable, but mid- and side channel are most prevalent. The tail of relatively finer sediment extending downstream of naturally occurring LOD (Hogan 1986) was not well developed in the present study sites. This is probably related to the amount of time over which the structures have been operating.

4.1.3 Sediment characteristics

Qualitative sediment analyses indicate that the surface textural expression is influenced strongly through sorting and geomorphic reach development. Over the reach scale, zones that are building undergo a "fining" of the surface sediment texture, as illustrated in Plate 4. Zones that are dormant become gradually coarser as the finer sediment supply is exhausted. This "coarsening" or armouring is shown in Plate 5.

On a local scale there is a tendency for the sediment texture to be more variable (absence of sorting) near log structures. Surface sediment textures are compared in Plate 6. The subsurface composition is characterized in Section 4.2.

PLATE 4. Fine sediments deposited after debris torrent in Southbay Dump Creek.

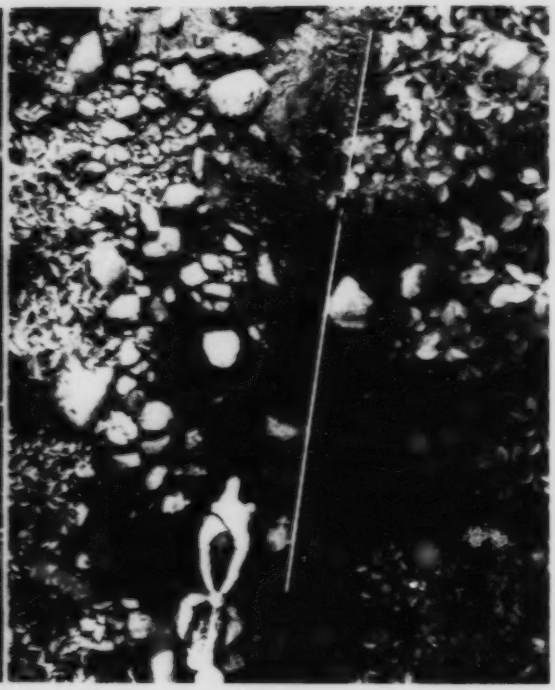


PLATE 5. Coarse sediments remaining after debris torrent in Macmillan Creek.

PLATE 6. Sediment sorting by LOD structures in Macmillan Creek.

4.2 Spawning Habitat

4.2.1 Gravel composition

Changes in spawning habitat were largely insignificant as indicated by F-test analyses. The high degree of variability in values of all gravel textural parameters, including median particle size (D_{50}), mean particle size (D), percent passing 3.36 mm, percent passing 0.85 mm, and Fredle Index, probably masked any changes on a local level.

The lack of significant primary (year) effects in gravel parameters, as induced by LOD installation, suggests that the LOD structures did not significantly affect overall gravel quality. Of the non-significant or inconsistent effects observed, intragravel dissolved oxygen appeared to drop between 1986 and 1987 at all streams. However, this decrease in intragravel DO was matched with similar reductions in DO values of surface water (Table 4). Had surface DO values been the same both before and after LOD , the intragravel DO values would likely have remained about the same. The F-test analysis also indicated a significant decrease in intragravel permeability with LOD placement at Southbay Dump Creek. This was, however, inconsistent with results at Sachs and Macmillan creeks. (Appendix 2, Table A2b).

A t-test analysis of Sachs Creek gravel composition data suggested that there were no significant changes in particle median diameter, mean diameter, fraction passing 3.36 mm, fraction passing 0.85 mm, Fredle Index, intragravel permeability, and intragravel dissolved oxygen from 1986 (pre-installation) to 1987 (post-installation) at LOD, gabion, or control sites (Table 4). However, non-significant changes were identified between years. Sediment particle size generally increased at LOD sites, largely due to changes occurring in the upstream LOD Site 5, whereas particle sizes at gabion and control sites tended to decrease. This may be from additional sediment sorting at the LOD sites. Effects at Sites 1 (LOD) and 2 (control) furthermost downstream were compounded by the release of 1-2 m of sediment when an old log jam failed over winter. Deposition of this material on Sites 1 and 2 was reflected in both DO and permeability values at these sites, having dropped proportionately more than at their counterparts (Sites 5 and 6) upstream of the failed log jam.

All study reaches, both before and after rehabilitation, had higher fines content than most Queen Charlotte Islands streams as measured in a synoptic survey. Values passing 0.85 mm and 3.36 mm (Table 4) exceeded averages for logged and mass wasted streams of 5.1 and 19.6%, respectively (Tripp and Poulin 1986b). The higher proportion of fines in study reaches was reflected in generally lower permeability values (Table 4) compared to those of other Queen Charlotte Islands streams averaging 38-39 mL/sec (Tripp and Poulin 1986b). Similarly, Fredle Index values were correspondingly lower than the average of 4.8 in other streams in the synoptic survey.

TABLE 4. Summary of gravel parameter values for Sachs, Macmillan, and Southbay Dump creeks before and after log installation, and results of t-test analysis for Sachs Creek values

Stream	Year	D_{50} (mm)	D (mm)	<3.36 mm (%)	<0.85 mm (%)	Fredle	Permeability (mL/sec[a])	DO (mg/L[b])
Sachs Creek:								
Logs	1986	9.04	8.06	24	9.8	1.06	13	7.1 (11.4-11.5)
	1987[c]	10.93	10.84	19	8.1	1.10	25[d]	4.5[e] (8.4-9.2)
significance[f]		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Gabions	1986	8.69	7.53	28	10.4	1.07	19	6.5 (11.3)
	1987	8.19	6.94	28	9.8	1.03	17	2.6 (8.0-8.7)
significance[f]		–	–	–	–	–	n.s.	n.s.
Controls	1986	8.69	7.71	27	10.5	1.09	18	5.3 (11.4-11.5)
	1987	7.32	6.31	31	11.0	1.04	22[g]	4.1[h] (7.8-8.4)
significance[f]		–	–	–	–	–	n.s.	n.s.
Macmillan Creek:								
	1986	8.30	8.02	25	7.7	1.08	30	7.6 (11.0-11.6)
	1987	7.95	7.43	25	6.8	1.05	30	7.3 (8.7-11.7)
Southbay Dump Creek:								
	1986	8.02	7.44	26	8.7	1.06	42	10.1 (11.1)
	1987	7.63	7.25	26	7.5	1.04	31	7.2 (7.4-9.8)

a Permeability values reported are expressed in mL/sec of water entering the permeability standpipe and have not been calibrated as per Terhune (1958).

b Intragravel Dissolved Oxygen values are accompanied by ranges of DO values in surface water taken at the same time (in parentheses).

c Changes shown at log sites are largely a function of the overwhelming changes at Site 5 from 1986 to 1987.

d Increase in permeability largely from increases at Site 5 (from 14 to 38 mL/sec) offset by a minor decrease at Site 1 (from 13 to 11 mL/sec), 1986 to 1987.

e Decline in intragravel DO a result of major declines in intragravel DO at Site 1 (from 8.6 to 2.1 mg/L) and a small increase at Site 5 (from 5.6 to 6.9 mg/L), 1986 to 1987.

f Significance at $p<0.05$ for t-test comparisons of means between years.

g Upward trend in 1987 driven by a major increase at control Site 6 (18-30 mL/sec), offset by a minor decrease at Site 2 (17-13 mL/sec), 1986 to 1987.

h Decline in intragravel DO a result of major declines in intragravel DO at Site 2 (from 7.5 to 3.6 mg/L) and slight increase at Site 6 (3.1-4.6 mg/L), 1986 to 1987.

4.2.2 Gravel scour

Scour monitors indicated mobilization of gravel during storm flows that would otherwise go unobserved from cross-sectional measurements. Gravel scour was monitored over the first winter after rehabilitation to observe stability of sediment storage areas upstream and scour pools downstream created during LOD site construction. Sites were excavated and pre-filled to approximate conditions anticipated at the sites after a season of storm flows, to prepare the sites for a large run of spawning salmon expected the first fall after rehabilitation.

A 47% loss of scour monitors, heavy runs of spawning salmon, and a log jam failure with resulting sediment release all complicated assessment of gravel scour at the LOD placement sites. Generally, the low gravel scour values reflected a mild winter (Table 5). Scour values were within the range measured in previous studies in Sachs Creek (Klassen 1984; Tripp and Poulin 1986b), but less than half of values measured in Macmillan and Southbay Dump creeks (27 and 35 cm, respectively; Tripp and Poulin 1986b). Average scour values at all streams (Table 5) suggested that the majority of chum and coho eggs deposited at the LOD sites (the majority buried between 20 and 30 cm; Tripp and Poulin 1986b) would not be scoured over the mild winter recorded.

The substantial difference between scour values upstream and downstream of LOD emplacements in Macmillan Creek (0.3 cm and 10.9 cm, respectively; Table 5) is inconsistent with those found in Southbay Dump Creek (10.5 cm and 8.0 cm, respectively). One explanation would be that the large run of chum spawners in Macmillan Creek preferred the plunge pool area downstream of the logs for spawning over the areas upstream, and effectively scoured the gravels during their redd building activity. A comparable process was lacking in Southbay Dump Creek, as virtually no spawners entered the stream.

TABLE 5. Summary of gravel scour results at study sites on Sachs, Macmillan, and Southbay Dump creeks

Stream	Number inserted	Monitors lost			Monitors recovered	
		Number scoured away[a]	Number buried[a]	Number unknown fate[a]	Number recovered	Average scour[b] (cm)
Sachs						
LOD sites	40	4	14	7	15	7.1
Gabions	30	0	0	0	30	7.6
Controls	12	0	5	0	7	8.8
Total	82	4	19	7	52	7.6
Macmillan						
Upstream	36	3	22	0	12	0.3
Downstream	36	3	10	5	18	10.9
Total	72	6	32	5	29	7.6
Southbay Dump						
Upstream	18	4	7	1	6	10.5
Between	6	0	3	0	3	0
Downstream	18	1	2	2	13	8.0
Total	42	5	12	3	22	8.8
Total	196	15	63	15	103	8.0

a Fate of lost monitors are estimates based on local streambed surface changes observed over winter.

b Average of number of monitors recovered, excluding those placed on the flood plain.

4.3 Rearing Habitat

Increases in juvenile salmonid rearing habitat quality with placement of structures were found in all study streams, but were more pronounced in the more severely damaged Macmillan and Southbay Dump creeks than in Sachs Creek. Summaries of habitat surveys conducted at all study streams are examined below.

4.3.1 Rearing habitat at Sachs Creek

Pool habitat at Sachs Creek showed substantial changes from 1986 to 1987. Pool area increased in the LOD rehabilitation, control, and gabion sites from the pre-construction low flow survey in 1986 to the 1-year post-construction survey in summer 1987 (Table 6). However, average maximum pool depth decreased at the LOD sites, whereas they increased at the control and gabion sites. This may have been a result of the creation of two shallow pools at the LOD sites and elimination of two pools at the other sites (Table 6), which affected the average depth.

Surface substrate at the LOD sites in Sachs Creek showed an overall shift to the finer and gravel fractions and a decrease in larger fractions with construction (Table 6). Changes in surface substrate at the control and gabion sites were relatively minor. The LOD sites had more representation in the gravel component before and particularly after LOD placement than did either the control or gabion sites, suggesting a high suitability for spawning.

Rearing cover characteristics underwent substantial changes with LOD site construction at Sachs Creek. There was a substantial increase in LOD cover at LOD rehabilitation sites (Table 6), with increases indicated also at gabion sites. Most of the observed changes at the gabion sites were from the re-flooding in 1987 of an old backwater pool that was highly inundated with LOD. Deep water habitat almost doubled with construction at the LOD sites. Overwinter cover at LOD sites almost trebled that at control sites over the year after construction.

Total habitat diversity did not change substantially in Sachs Creek from 1986 to 1987. Pool habitat diversity decreased marginally at LOD sites, decreased substantially at control sites, and increased at gabion sites.

TABLE 6. Instream, low-flow habitat conditions in LOD rehabilitation, control, and gabion sections of Sachs Creek, 1986 and 1987

Variable	1986			1987		
	Rehab.	Control	Gabion	Rehab.	Control	Gabion
Stream length (m)	125.0	93.5	103.5	125.0	93.5	103.5
Wetted area (m^2)	948.1	501.5	1044.5	953.1	574.9	1017.3
Pool characteristics:[a]						
Pool area (%)	40.5	28.9	82.3	69.6	51.8	89.4
Pool depth[b]	81	76	71	72	97	83
Pool no.	11	9	11	13	7	9
No. types[c]	3	4	4	3	2	4
Major type	BP	BP/LP	LP/BP	UP/LP	BP/LP	BP/LP
Surface substrate:						
% fines (<5 mm)	20	16	22	26	18	20
% gravel (5-63 mm)	52	50	41	57	44	42
% larges (>63 mm)	28	34	37	17	38	38
Cover characteristics:[d]						
LOD	7.8	6.3	5.2	12.2	5.2	7.5
SOD	1.5	0.9	0.9	1.0	1.5	1.4
Depth	23.0	47.2	61.5	41.9	48.5	82.9
Rock	0.8	0.7	4.7	0.1	0.5	0.5
Undercut banks	1.1	2.4	2.3	1.5	5.3	1.2
Turbulence	0.0	0.3	1.2	0.1	2.6	4.5
Vegetation	5.3	20.1	1.0	4.4	11.1	2.0
Total[e]	39.5	77.9	76.8	61.2	74.7	100.0
Total winter[f]	29.1	11.2	76.4	52.2	15.9	89.3
Habitat diversity (H')[g]						
Total	2.10	1.81	2.08	2.06	1.85	2.15
Pool	1.43	1.59	1.44	1.27	0.31	1.73

a Pools created by gabions are considered LOD pools for this analysis.

b Average maximum pool depth minus average maximum riffle depth.

c Six pool types as follows: LP = lateral scour pool, BP = backwater pool, PP = plunge pool, UP = underscour pool, DP = dam pool, CP = "capped" side pool.

d Sum of percentages in each of above cover types.

e Expressed as percent of wetted area.

f Sum of percent LOD, undercut banks, rock, and deepwater cover in LOD and gabion controlled pools.

g Habitat diversity index $\Sigma H' = \frac{3.32193 (A \log A - a_i \log a_i)}{A}$

where: A = total wetted area, a_i = wetted area of the i^{th} habitat type (riffles, glides, each pool type).

4.3.2 Rearing habitat at Macmillan Creek

Pool characteristics underwent substantial changes with LOD site and blast pool construction at Macmillan Creek. Pool area increased an order-of-magnitude in the rehabilitation section (including the blast pools), and remained the same in the control section (Table 7). Similar increases in net pool depth (maximum pool depth less riffle depth) were found in the rehabilitation section and stayed the same in the control section. Pool number more than doubled in the rehabilitation section and increased slightly in the control section. The number and type of pools similarly increased in the rehabilitation section.

Surface substrate observations in Macmillan Creek indicated a shift in 1987 to finer fractions in both rehabilitation and control sections. The increased proportion of fines reflected the influence of the LOD in trapping a wider range of sediment sizes.

Cover characteristics improved substantially with LOD site construction in Macmillan Creek. The amount of LOD cover more than trebled with LOD site construction in the rehabilitation section, whereas it decreased by more than 50% in the control section (Table 7). Small organic debris increased in the rehabilitation section while decreasing in the control section. Similarly, deep water cover increased in the rehabilitation section and decreased in the control section. Total cover in the rehabilitation section increased with LOD site construction, and decreased in the control section. Total winter cover, critical for overwinter fry survival, increased about 20 times in the rehabilitation section, while decreasing in the control section. Both total and pool habitat diversity increased substantially in the rehabilitation sections while decreasing in the control sections.

The two blast pools in a side channel tributary of Macmillan Creek averaged 4-5 m in diameter, with maximum depths of 95 and 101 cm. The entire pool area provided deepwater cover. Although the ground water level appeared to be at the surface before blasting, it dropped to about half of the crater depth after blasting. Access for fish passage was achieved by connecting ditches being dug to the water surface in the pools. The ground water source posed a concern for rearing values in that depth-integrated dissolved oxygen values during low flows 1 year after construction were only 4.8 mg/L in the upstream pool, increasing to 7.4 mg/L in the downstream pool, compared to stream values of 10.0 mg/L. A series of several pools may be required to bring dissolved oxygen values to desirable levels for rearing habitat if low-oxygen groundwater sources are used.

TABLE 7. Instream, low-flow habitat conditions in LOD rehabilitation and control sections of Macmillan Creek, 1986 and 1987

Variable	1986		1987	
	Rehab.	Control	Rehab.	Control
Stream length (m)	267.2	177.0	267.0	171.0
Wetted area (m^2)	872.0	570.2	933.1	620.1
Pool characteristics:				
Pool area (%)	3.8	19.4	35.9	17.6
Pool depth[a]	-3	20	37	23
Pool no.	11	13	27	15
No. types[b]	3	4	6	3
Major type	BP	LP/BP	PP/BP	BP/LP
Surface substrate:				
% fines (<5 mm)	7	7	18	11
% gravel (5-63 mm)	38	35	34	40
% larges (>63 mm)	55	59	48	49
Cover characteristics[c]:				
LOD	2.5	13.7	9.4	5.5
SOD	0.8	3.2	1.7	0.8
Depth	11.3	22.0	14.9	9.6
Rock	8.4	9.8	5.5	4.7
Undercut banks	0.1	1.3	0.1	1.0
Turbulence	1.5	2.6	4.5	3.9
Vegetation	11.3	10.1	10.4	22.5
Total[d]	35.9	62.7	46.5	48.0
Total winter[e]	1.2	19.3	23.9	13.1
Habitat diversity (Hi')[f]				
Total	0.87	1.40	2.18	1.16
Pool	0.56	1.26	1.49	0.30

a Average maximum pool depth minus average maximum riffle depth. Negative values may be found where backwater pools are shallower than the adjacent riffles.

b Six pool types as follows: LP = lateral scour pool, BP = backwater pool, PP = plunge pool, UP = underscour pool, DP = dam pool, CP = "capped" side pool.

c Expressed as percent of wetted area.

d Sum of percentages in each of above cover types.

e Sum of percent LOD, undercut banks, rock, and deepwater cover in LOD controlled pools.

f Habitat diversity index $\Sigma H' = \frac{3.32193 (A \log A - a_i \log a_i)}{A}$

where: A = total wetted area, a_i = wetted area of the i^{th} habitat type (riffles, glides, each pool type).

4.3.3 Rearing habitat at Southbay Dump Creek

The changes in cover characteristics with LOD site construction were similar in Southbay Dump Creek to those found in Macmillan Creek. Pool area almost trebled in the rehabilitation section (including the blast pools) of Southbay Dump Creek, whereas it decreased in the control section (Table 8). Pool depth, pool number, and number of pool types all doubled or more in the rehabilitation section while decreasing substantially in the control sections.

The surface substrate observations indicated an overall shift to finer sediments in the rehabilitation sections and a shift to larger substrates in the control section.

Cover characteristics underwent major changes in Southbay Dump Creek with site construction. The LOD cover increased slightly in the rehabilitation section while declining substantially in the control section (Table 8). The low-flow conditions during which the habitat survey was conducted resulted in the dewatering of numerous segments of the stream in the rehabilitation section, largely because the stream had been choked with sediments deposited by the rehabilitation in a series of debris torrents. Frequently, LOD was present in the dry channel and was not included in the survey. Greater LOD cover values would have been seen had the survey been conducted during higher flows. Small organic debris decreased in both rehabilitation and control sections. Deep water cover increased substantially in the rehabilitation section while decreasing in the control section. Overhanging vegetation decreased substantially in the rehabilitation section, probably from diversion of the main channel away from the vegetated stream banks and vegetation removal during blasting. The effect of the low flows and dewatering is seen in the total cover values, decreasing in both rehabilitation and control sections. However, the critical overwinter cover values in the rehabilitation section more than doubled, while decreasing substantially in the control section.

Habitat diversity, both in total and at pools, increased in the rehabilitation section and decreased in the control section.

The two blast pools at Southbay Dump Creek had similar dimensions to those at Macmillan Creek, averaging 5-5.5 m diameter, with maximum depths of 91 and 108 cm. Unlike at Macmillan Creek, a perennial side channel flowed through the pools, providing oxygen-rich water to the pools. Access ditches were again dug to provide fish passage to the pools, as the water levels dropped with the blasting.

TABLE 8. Instream, low-flow habitat conditions in LOD rehabilitation and control sections of Southbay Dump Creek, 1986 and 1987

Variable	1986		1987	
	Rehab	Control	Rehab	Control
Stream length (m)	169.0	213.5	170.0	216.5
Wetted area (m^2)	433.7	634.8	459.8	592.7
Pool characteristics:				
Pool area (%)	13.8	17.5	37.0	9.7
Pool depth[a]	20	13	47	18
Pool no.	7	18	17	13
No. types[b]	3	5	6	2
Major type	LP	LP/BP	PP	LP/BP
Surface substrate:				
% fines (<5 mm)	4	17	18	10
% gravel (5-63 mm)	43	46	39	49
% larges (>63 mm)	53	37	43	41
Cover characteristics:[c]				
LOD	8.9	18.1	11.5	11.6
SOD	2.7	1.4	1.6	0.9
Depth	5.8	6.3	10.2	3.1
Rock	5.6	2.0	4.0	3.4
Undercut banks	0.5	0.4	0.1	0.7
Turbulence	0.5	0.4	0.5	0.4
Vegetation	16.8	23.9	7.9	22.2
Total[d]	40.8	52.4	35.8	42.3
Total winter[e]	7.4	17.0	19.8	6.3
Habitat diversity (H')[f]				
Total	1.35	1.48	2.26	1.27
Pool	1.16	0.93	2.03	0.67

a Average maximum pool depth minus average maximum riffle depth.

b Six pool types as follows: LP = lateral scour pool, BP = backwater pool, PP = plunge pool, UP = underscour pool, DP = dam pool, CP = "capped" side pool.

c Expressed as percent of wetted area.

d Sum of percentages in each of above cover types.

e Sum of percent LOD, undercut banks, rock, and deepwater cover in LOD controlled pools.

f Habitat diversity index $\Sigma H' = \frac{3.32193 (A \log A - a_i \log a_i)}{A}$

where: A = total wetted area, a_i = wetted area of the i^{th} habitat type (riffles, glides, each pool type).

4.3.4 Rearing habitat at Bonanza Creek tributary

The blast pools created in Bonanza Creek tributary substantially increased habitat available to juvenile salmonids. The most obvious change in habitat due to blasting was an increase in total wetted area (from 111 to 313 m^2 in rehabilitation sections [Table 9] – a 2.8-fold increase, compared to 218-268 m^2 in control sections – a 1.2-fold increase) and net pool depth (a 3.3-fold increase in rehabilitation sections compared to a 1.2-fold increase in control sections). Average blast pool wetted area was 31.5 m^2, with an average depth of 0.95 m. Average blast pool wetted area in non-dewatered pools was 43.0 m^2 with an average depth of 1.21 m. Figure 15 illustrates the plan view of a typical non-dewatered blast pool. Additional examples of blast pools configurations are in Appendix 3.

Total cover in control and rehabilitation sections increased from 1986 to 1987 – 19.9% in rehabilitation sections and 11.0% in control sections. Increases in rehabilitation sections were due to increased deep water cover (from 1.4 to 51.2% of wetted area), although this was offset by declines in large organic debris (LOD), small organic debris (SOD), and overhanging vegetation (from 44.2 to 20.8%). Overhanging vegetation was lost at all blast sites. Depth, SOD, overhanging vegetation, and undercut bank cover also increased in control sections (from 25.1 to 48.5%) due to higher flows. The loss of LOD cover, however (from 25.1 to 12.7% of wetted area), was attributed to extra dewatering in the lowermost control section.

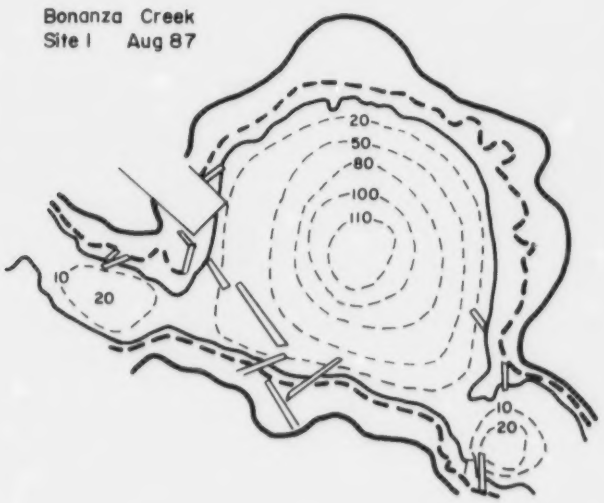


FIGURE 14. One-year post-construction plan view map of Blast Pool Site 1, Bonanza Creek, August 1987. Depth contours in centimetres. Pool diameter approximately 5 m.

TABLE 9. Instream, low-flow habitat conditions in LOD rehabilitation and control sections of Bonanza Creek tributary, 1986 and 1987

Variable	1986		1987	
	Rehab.	Control	Rehab.	Control
Stream length (m)	153	189	153	189
Length dewatered (m)	39	21	33	51
Wetted area (m^2)	111	218	313	268
Pool characteristics:				
Pool area (%)	51.5	59.5	78.7	71.9
Pool depth[a]	29	44	95	51
Pool no.	6	10	12	6
Cover characteristics:[b]				
LOD	20.7	25.1	9.6	12.7
SOD	19.3	12.1	8.5	15.4
Depth	1.4	6.1	51.2	9.4
Undercut banks	2.8	4.3	6.3	14.3
Vegetation	4.2	2.6	2.7	9.4
Total[c]	48.4	50.2	78.3	61.2
Total winter[d]	20.8	28.6	15.8	28.2

a Average maximum pool depth minus average maximum riffle depth.

b Expressed as percent of wetted area.

c Sum of percentages in each of above cover types.

d Sum of percent LOD, undercut banks, and deepwater cover in LOD controlled pools.

There was no difference in winter cover from 1986 to 1987 in control sections. Blast pools were not considered as winter cover because they were not LOD-controlled, that is, formed as a result of scouring around LOD. Winter cover consequently declined in rehabilitation sections because increase in deep water cover was not counted in blast pools and because LOD, SOD, and undercut banks were lost in blast pools.

Bonanza Creek tributary dewaters in lower sections during summer because of excess sediments. Dewatering probably occurs every year; it certainly was observed both in 1986, before pond construction, and in 1987, a year after construction. Although flows on sampling days were not recorded with a staff gauge, the discharges were greater in 1987 (August) than in 1986 (August). Despite the increased flows, the lower reaches still were dewatered in 1987. Blast holes, especially the lowermost two, may have increased the degree of dewatering by disturbing or breaking through

an impermeable layer below the streambed in the downstream rehabilitation and control, gravel-bedded sections. Pond construction did not appear to affect the upstream (silt/sand-bedded) sections. Total length of control sections dewatered increased from 21 to 51 m. In contrast, total length of rehabilitation sections dewatered decreased from 39 to 33 m from pre- to post-construction surveys. Decreases in length dewatered in rehabilitation sections were partly due to increased pool area in isolated blast holes. Otherwise, dewatered lengths of rehabilitation sections remained comparable between years. An additional 30 m of control section dewatered upstream of the second lowermost blast pool.

4.4 Fish Use at Rehabilitation Sites

Major runs of adult salmon ascended Sachs and Macmillan creeks within weeks of site construction activities in 1986. Adult pink and chum salmon were observed holding in the pools created during construction, and spawning in tails of these and other pools. In one streamside traverse of Macmillan Creek, of the 272 adult chum observed, 78 (29%) were holding near or spawning in gravels associated with the 12 log emplacements within 10 m upstream or downstream of the sites, averaging 0.65 fish per lineal metre rehabilitated. This compares favourably to the 0.51 fish observed per lineal metre of stream between the sites.

Juvenile salmonids also responded positively to the LOD emplacements and blast pools. These results are discussed separately below.

4.4.1 Juvenile fish response in Sachs Creek

Interpretation of the juvenile salmonid population estimates must take into account the ongoing seasonal decline in juvenile populations. Populations are compared between LOD sites and gabion and control sites to account for this seasonal population decline and fluctuations between years. For Sachs Creek, gabion sites were little affected by LOD placement and can be used as a relative control. The designated controls are not as satisfactory, owing to low population densities and to sediment inundation at the lower control. Before construction, the LOD sites had about 50% the coho population of the gabion sites (Table 10). About 3 weeks after construction, coho populations at all sites had decreased, but proportionately less so at the LOD sites than at the gabion sites. The control sites countered the expected trend by increasing, perhaps from preferential habitat selection later in the season. The early season trapping survey in April 1987 indicated a higher catch per trap rate at LOD sites than at gabion sites. The 1-year post-construction survey in August 1987 similarly showed that the LOD site/gabion site coho populations ratio was higher relative to the pre-construction values, suggesting that juvenile coho found the LOD sites at Sachs Creek to be a more favourable habitat than before construction.

TABLE 10. Pre- and post-construction juvenile fish population estimates in study sections of Sachs Creek, 1986 and 1987

Date	Stream section	Length (m)	Coho	Rainbow	
			0+	0+	≥1+
July 14, 1986	LOD	125	1419±137	445±222	49±24
(Pre-construction)	Gabions	103.5	2839±182	110±108	80±36
	Controls	93.5	114±84	243±138	80±47
September 15, 1986	LOD	125	885±77	372±81	141±52
(Post-construction)	Gabions	103.5	1250±91	349±54	39±18
	Controls	93.5	396±67	286±56	20±10
April 26, 1987	LOD	(12 traps)	15/trap	21/trap[a]	
	Gabions	(5 traps)	10/trap	4/trap[a]	
	Controls	(6 traps)	2/trap	0/trap[a]	
August 20, 1987	LOD	125	754±53	>314[b]	48±14
(1-yr post-	Gabions	103.5	1227±83	>169[b]	92±20
construction)	Controls	93.5	499±35	>139[b]	50±13

[a] Juvenile trout are in a 1-1+ category at this time of year.

[b] 0+ rainbow trout were not marked during this estimate; values indicated were numbers caught in one pass.

Juvenile rainbow trout populations showed a strong initial response to LOD site construction. Within weeks of construction, ≥1+ rainbow trout populations had almost trebled at the LOD sites but showed major declines at the gabion and control sites (Table 10). Spring trapping surveys continued to show high LOD site use by rainbows compared to that in gabion and control sites. However, 1 year after construction, the rainbow populations had returned to the pre-construction levels at all sites, perhaps from infilling of the favoured habitat at the LOD sites over the winter.

4.4.2 Juvenile fish response in Macmillan Creek

Juvenile coho responded very positively to LOD emplacements at Macmillan Creek. Within 1 month of site construction, 0+ coho numbers doubled at rehabilitation features, unlike the declines

found at control sites (Table 11). This suggests that there was an active migration to the sites shortly after construction. The LOD sites remained attractive to juvenile coho after the first winter, maintaining densities an order-of-magnitude higher than in the control section. Summer densities at LOD features 1 year after construction again doubled those found in control sections. These increases in juvenile densities are significant, as there were no significant differences between the rehabilitation features and control section densities in the pre-construction survey.

Sample numbers of other salmonids were insufficient to generate population estimates.

The concept of rehabilitation features and rehabilitation sections was introduced to illuminate that the LOD structures were attracting fish to the rehabilitation sections. Control values are most appropriately compared to rehabilitation features, as the rehabilitation sections contained reaches of unimproved stream.

The blast pools at Macmillan Creek held three and seven juvenile coho, respectively, in the 1-year post-construction survey. It is interesting that only a few fish selected this habitat at the depressed oxygen values found in this water (Section 4.3.2).

TABLE 11. Pre- and post-construction juvenile coho densities per lineal metre of stream in study sections of Macmillan Creek, 1986 and 1987

Date	Stream section	0+Coho	
		No. /m of stream (±95% conf. lim.)	Poisson distribution
July 9, 1986	Rehab section	3.60±0.76	(2.77-4.73)
(Pre-construction)	Rehab features	2.87±0.66	(2.17-4.00)
	Control section	2.63±0.79	(1.88-3.81)
September 26, 1986	Rehab section	2.31±0.64	(1.66-3.27)
(Post-construction)	Rehab features	5.90±1.58	(4.22-8.62)
	Control section	1.74±0.43	(1.02-2.49)
April 21, 1987	Rehab section	0.65±0.23	(o.44-1.13)
(Post-winter)	Rehab features	2.05±0.73	(1.38-3.58)
	Control section	0.21±0.11	(0.10-0.50)
August 17-19, 1987	Rehab section	1.25±0.21	(0.97-1.68)
(1-yr post-construction)	Rehab features	2.43±0.41	(1.85-3.36)
	Control section	1.14±0.26	(0.82-1.71)

4.4.3 Juvenile fish response in Southbay Dump Creek

The LOD sites in Southbay Dump Creek also attracted greater densities of juvenile salmonids. The 0+ coho densities at LOD features more than doubled within 1 month of construction, whereas densities in the control section declined slightly (Table 12). By 1 year after construction, juvenile coho densities had increased by an order-of-magnitude, whereas densities in the control section had remained about the same. However, comparisons between years are not recommended, because of the stream cutting through a major log jam separating control and rehabilitation sections over winter 1986-87 that was previously impassable at most flows. Juveniles had free access over all the study sections in spring-summer 1987, but in spring-summer 1986 they did not. Juvenile coho densities were comparable between Southbay Dump and Macmillan creeks after construction and after downcutting occurred around the log jam.

Juvenile Dolly Varden densities at study sections did not reflect any major response to LOD site construction. Higher densities were found in the rehabilitation section rather than in the control section, probably because of the higher slope gradient habitat located in the rehabilitation section upstream.

Blast pools at Southbay Dump Creek held more juveniles (33 and 46 0+ coho) than did their counterparts in Macmillan Creek (Section 4.4.2). This may be because the surface water source available at these pools provided a higher dissolved oxygen content.

TABLE 12. Pre- and post-construction juvenile fish densities per lineal metre of stream in study sections of Southbay Dump Creek, 1986 and 1987

Date	Stream section	Length (m)	No. /m of stream (±95% conf. lim.) 0+ Coho	Dolly Varden
July 26, 1986 (Pre-construction)	Rehab section	169	0.34±0.08	0.77±0.27
	Rehab features	146	0.28±0.11	1.13±0.96
	Control section	213	2.21±0.48	- NA -
Sept. 22, 1986 (Post-construction)	Rehab section	174	0.46±0.14	0.55±0.34
	Rehab features	47	0.88±0.41	0.51±0.42
	Control section	213	1.61±0.29	0.03±0.02
August 12, 1987 (1-yr post-construction)	Rehab section	170	1.61±0.18	0.34±0.30
	Rehab features	49	3.34±0.31	0.65±0.56
	Control section	217	1.72±0.40	0.08±0.09

4.4.4 Juvenile fish response in Bonanza Creek tributary

Blast pools significantly increased the summer standing crop of all age classes of coho (0+, 1+) and Dolly Varden (0+) in rehabilitation sections (Tables 13 and 14). Before construction, densities in control sections were statistically higher ($p<0.05$) than those in rehabilitation sections. Both sections, however, had low densities overall. One year after construction, densities of all fish combined were substantially (4.9 times) higher in rehabilitation sections, mainly because of high densities in blast pools. Overall densities were 3.3 fish per metre of stream in rehabilitation sections (±1.20) compared to 0.68 fish per metre of stream (±0.40 fish) in control sections. When expressed as fish per square metre, differences were slightly lower (3.4 times more fish in rehabilitation sections), but still highly significant.

Blast pools were highly favoured habitats in summer low flows – 87.8% of fish in rehabilitation sections were in blast pools, regardless of whether numbers were expressed as fish per metre of stream or fish per square metre. By comparison, blast pools represented 60.3% of the wetted rehabilitation section area and 36.7% of the wetted rehabilitation section length.

Winter data on fish are not strong, but they suggest that blast pools were not favourable habitat, or at least no more favourable than non-blast pools and glides. Altogether, 31 coho and 5 Dolly Varden were captured in 12 minnow traps set for 16.5 hours in blast pools, for an average catch per trap of 3.0 fish. Approximately the same number of fish were captured (3.6 fish/trap) in non-blast pools and glides. Absence of differences may be attributable to lack of complex cover (LOD, undercut banks, SOD) in pools compared to that in other areas, thus offsetting the benefits offered by deep water.

This large number of 0+ coho present in Bonanza Creek tributary in August 1987 (1 year after construction) means the tributary is sometimes an important spawning and rearing area, not just an overwintering area. In streams like this, the greatest benefit of new blast pools may be substantial increases in summer rearing habitat and standing crop as opposed to increased winter habitat and overwinter survivals. Pools were probably too simple to serve as good overwintering habitat. After pools are blasted, they should be complexed with instream and overhanging debris. Then the 3.4- to 4.9-fold increases observed in summer standing crop in rehabilitation sections could be translated into comparable increases in overwinter survival and smolt production.

By creating deep pools, blasting may help offset summer losses due to dewatering. They may also help offset early losses caused when fish first move into off-channel habitats in fall during the first freshet, subsequently dying if the stream dries up before the next freshet. Coho obviously favour these small streams, but they take a gamble. The streams are ephemeral, regularly drying up, mostly in summer, but often starting or stopping between early fall rains or during cold winters. New deep pools can reduce some of the risks associated with these conditions by providing deep water havens during low-flow periods.

TABLE 13. Pre- and post-construction juvenile fish densities per lineal metre of stream in the Bonanza Creek tributary, August 1986 to August 1987

Date	Stream section	Coho 0+	Coho 1+	Dolly Varden 0+	Total
		No. fish/m of stream (±95% conf. lim.)			
August 29, 1986 (Pre-construction)	Rehab.	0.13±0.03	0.04±0.01	0.10±0.02	0.27±0.06 [a]
	Control	0.21±0.03	0.10±0.03	0.13±0.08	0.44±0.14
August 25, 1987 (Post-construction)	Rehab.	2.72±0.20	0.16±0.05	0.42±0.95	3.30±1.20 [b]
	Control	0.65 ±0.40	0.02±0.00	0.01±0.00	0.68±0.40

[a] Rehabilitation sections not significantly different from control sections at $p<0.05$.

[b] Rehabilitation sections significantly different (4.9 times greater) from control sections at $p<0.05$.

TABLE 14. Pre- and post-construction juvenile fish densities per square metre of stream in the Bonanza Creek tributary, August 1986 to August 1987

Date	Stream section	Coho 0+	Coho 1+	Dolly Varden 0+	Total
		No. fish/m^2 of stream (±95% conf. lim.)			
August 29, 1986 (Pre-construction)	Rehab.	0.18±0.04	0.05±0.01	0.14±0.03	0.37±0.08 [a]
	Control	0.18±0.03	0.09±0.02	0.11±0.07	0.38±0.12
August 25, 1987 (Post-construction)	Rehab.	1.33±0.10	0.18±0.02	0.21±0.47	1.62±0.59 [b]
	Control	0.46 ±0.28	0.01±0.00	0.00±0.00	0.47±0.28

[a] Rehabilitation sections not significantly different from control sections at $p<0.05$.

[b] Rehabilitation sections significantly different (3.4 times greater) from control sections at $p<0.05$.

4.5 Construction Time and Costs

4.5.1 LOD structures

The average cost per site for a LOD structure in the study streams ranged from $639.00 in Macmillan Creek to $1223.00 in Sachs Creek. Overall cost for the three study streams averaged $790.00 per site (Table 15). Site costs included wages for one biologist and one assistant onsite at all times during the instream work, meals, lodging, and vehicle rental. In all cases, the rates were standard costs and are believed to accurately reflect the cost a forest company or agency would pay for the operational phase of adding stable debris to small streams if all of the work were contracted out in 1986/87 dollars. Costs not included in these figures were those associated with planning or undertaking the research aspects of the project, and the value of the logs and cable used in the construction. Planning included pre-construction site inspections, development of research working plans, obtaining permit approvals, and development of the LOD requirements for the stream. Logs used in this study were all either boom logs culled from nearby booming grounds, windthrows, or beach logs washed up on nearby shores. Cable used to anchor the logs in position was old, discarded cable found abandoned on logging roads.

Costs for heavy equipment, including those for transportation, standby time, down time, and machinery cleaning represented approximately 49% of the total construction costs. Of this, time spent collecting and transporting the logs to each site accounted for 12% of the total costs, while time spent actually placing and anchoring the logs at each site accounted for 27% of the costs.

Differences in average construction costs between streams were due primarily to differences in access, availability of logs, and the complexity of the LOD structures selected for each site. For example, in Sachs Creek, extra time and equipment were required to clear an old 150 m skid trail to reach the stream and bring logs to the site. In Macmillan Creek, there was an additional cost of $315.00 incurred when a log skidder was required to retrieve logs off a beach located at the stream mouth. Sachs Creek also contained a higher number of the more complex structures tested, and thus required more logs. In addition, Sachs Creek lacked proper anchor points and required at least one deadman anchor at each of the sites.

Construction costs in each stream were more closely related to the number of logs used (including deadman anchors) than to the number of sites. Average costs per log were:

Southbay Dump Creek	**$ 370.00**
Macmillan Creek	**$ 334.00**
Sachs Creek	**$ 306.00**

Reduction in the price per log was attributed largely to experience gained by the crew and backhoe operator during the course of the project. Average cost for all the sites was $341.00 per log.

Construction costs of multiple-log arches in Sachs Creek ($1223) were below that incurred for the gabion weirs in Sachs Creek ($1500-2600) in $1982 (Klassen 1984).

TABLE 15. Summary of on-site costs for installing LOD structures in Sachs, Southbay Dump, and Macmillan creeks, July 1986 (in 1986 dollars)

	Sachs		Southbay		Macmillan		Total
	Time	Cost	Time	Cost	Time	Cost	cost
Personnel							
Biologist		1056		973		1601	3630
Assistants		608		561		921	2090
				Sub Total			**5720**
Heavy equipment @ $65-80/hr							
Mobilization	3.5	280	3.5	280	8.5	705	1265
Log delivery	14.0	890	9.5	760	6.5	465	2115
Log placement	14.0	1120	14.0	1120	31.5	2520	4760
Standby time	0.5	20	1.0	40	2.0	80	140
Downtime	0.0	0	1.0	80	0.0	0	80
Cleaning	0.0	0	1.0	80	0.0	0	80
				Sub Total			**8440**
Other disbursements							
Truck @ $90/day	4	360	4	360	6	540	1260
Meals/lodging @ $70/day	8	560	8	560	12	840	1960
				Sub Total			**3220**
Total cost		**4894**		**4814**		**7672**	**17 380**
No. sites developed		4		6		12	22
No. logs		10		11		21	43
No. deadman		5		2		2	9
Cost per site		**1223**		**804**		**639**	**790**

4.5.2 Blast pools

Average cost of constructing the blast pools using explosives was $492.00 per pool (Table 16), of which $230.00 was for personnel including an explosives expert, a biologist, and two assistants to pack the explosives into the rehabilitation sites. Transportation and per diem for several crew was $111.00. Cost of the explosives averaged $151.00 per site which covered approximately three bags of Amax, three sticks of powder (Loggers Special 75%), and 15 m of detonation cord for each pool constructed. As with the log work, construction efficiency improved with increased experience in blasting. Generally speaking, few blasters in the forest industry are required to blast holes or trenches in their normal course of duties.

TABLE 16. Summary of on-site costs for blasting 10 pools in side channels (Macmillan and Southbay Dump creeks) and tributary streams (Bonanza Creek), August 1986

Personnel		Total
Biologist		792.00
Blaster		600.00
Assistants (2)		912.00
		2304.00
Disbursements		
Truck/fuel	3 days @ $90/day	270.00
Meals/lodging	12 days @ $70/day	840.00
Explosives	28 bags Amax @ $42.84/bag	1200.00
	1 box powder (75%)	118.00
	1.5 rolls detonating cord	171.00
	10 fuses (2 m, non-electric)	18.00
		2617.00
	Grand total	$4921.00
	Total per site	$492.00

4.6 Short-term Impacts

Short-term impacts of site construction were detected. The construction generated suspended sediments that were visually apparent for >500 m downstream. Sediments also dropped out of suspension and accumulated in quiet water areas along the stream. These effects are discussed in detail below.

4.6.1 Suspended sediments

At Sachs Creek, suspended sediment levels were 120 mg/L 65 m downstream of active site construction, and dropped to a range of 1-6 mg/L at distances of 400-900 m downstream. At Macmillan Creek, spot suspended sediment levels showed 1860 and 1330 mg/L immediately downstream of site construction, dropping to 37 and 38 mg/L approximately 100-200 m downstream within 1 hour. At Southbay Dump Creek, a spot sample of 1580 mg/L was recorded immediately downstream of site construction activity, with levels dropping to 12 mg/L at about 400 m downstream within 1 hour. Suspended sediments were observed to drop quickly out of the water column, and streamwater returned to normal clarity over the entire stream within 3-4 hours after construction stopped. These short-term suspended sediment bursts probably had minor effects on fish populations within 50-100 m of construction for several hours, such as influencing feeding behaviour (Environment Canada, Environmental Protection Service 1983) and temporarily inducing a coughing reflex (Berg 1982).

4.6.2 Settleable sediments

As with suspended sediments, accumulation of settleable sediments also rapidly decreased downstream of construction. At Sachs Creek, sediment accumulations decreased about 90% from 0.33 - 0.40 gm/cm^2 measured 25-30 m downstream of construction, to about 0.01 - 0.04 gm/cm^2 measured 80 m further downstream (Figure 14). No sediment accumulation was detected by 230 m downstream. Where sediment was detected, more accumulated in pool samples (>2 times) than in riffle samples. At Macmillan Creek, where construction occurred at several locations upstream of the sediment traps, the overall sediment accumulation was 0.25 gm/cm^2 in pools (range = 0.58 - 0.09; n=12) and 0.17 gm/cm^2 in riffles (range = 0.52-0.01; n=11). The sediments persisted until the first minor freshet following construction, which removed all observable accumulations. The settleable sediments probably affected benthic production in pool areas immediately downstream of construction for the period before the first freshet, covering the substrate and organisms growing on them. Salmonid food production in riffle areas was considerably less affected, with the faster flowing water preventing most sediment accumulation.

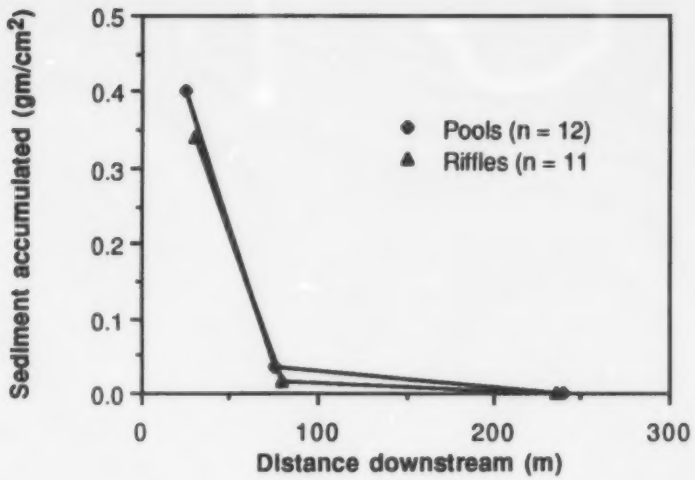


FIGURE 15. Sediment accumulated in sediment traps downstream of construction at Sachs Creek.

4.6.3 Access

Heavy equipment access routes followed different patterns at the three study streams. At Sachs Creek, access from roadways was entirely by overbank areas, with entry to the stream channel in pre-existing gaps in riparian vegetation. No disturbance to the streambanks occurred, except at log insertion points. At Macmillan Creek, heavy equipment reached the stream by the beach and by a short trail cut in an overbank area from the roadway. Further access to the sites was generally by self-made overbank trails that crossed the stream at four locations. Local stretches of riparian alder were disturbed at these stream crossings. Broken vegetation was later removed and the access trails grassed. At the more recently torrented Southbay Dump Creek, stream access was generally along the stream channel, keeping to gravel bar areas where they existed. Riparian vegetation was not disturbed, except at the blast sites in a tributary channel. All disturbed areas were grassed.

4.7 Structure Durability and Performance

During low flow periods, the streambeds are geomorphically stable. The bed and channel characteristics develop through sediment transport, accretion, and erosion during the much greater winter flood flows, where velocities may reach 3-3.5 m/sec. Since the LOD structures also develop their geomorphic features during high flows, their ability to remain submerged and stable during such flows is paramount to their success. Deadman anchors buried at the apex of the arch structures, together with bracing, cabling, and partial burial, were employed as simple practical means of building stability into the LOD placements.

Straight and steep torrented channels are characterized by a generally continuous riffle sequence with limited pools. The only irregularity in the channel morphology occurs where debris jams have blocked the channel, resulting in bank erosion, accretion upstream, and bed scour downstream. Although these geomorphic features are the aim of the LOD structures, the large size of the jams presents an impassible barrier to fish migration and leads to downstream channel damage when the unstable structures fail.

The need in restabilizing torrented channels is to dissipate energy in a controlled manner through regularly placed drop structures. The controlled hydraulic characteristics of the stream result in the formation of relatively stable pools, riffles, and channel bars. The groups of LOD structures are aimed at generating this needed stability and providing the hydraulic diversity desirable for fish habitat.

The placement and orientation of the logs within the streambed affect the local flow conditions. The "scour" logs act as drop structures by changing the flow direction normal to the log as the flow becomes supercritical over the structure. The high velocity jet created in the supercritical flow region results in a scour hole or plunge pool immediately downstream of the log or structure. An inappropriate orientation of the log could lead to erosion of the channel sides and possible outflanking of the log where it meets the stream bank. The arch structures avoid this problem by centring flow in the channel.

Single log structures can be used to create some sinuosity in the otherwise linear channel of the torrented stream. When performing as drop structures, with flow passing over the log, the single logs are similar to the arch structures in that they develop sediment storage on the upstream side and a scour pool on the downstream side. The virtue of the single log is simplicity, although stability of the log can be a problem. A log shorter than the channel width requires burial or anchoring of the mid-channel end with a deadman; a log spanning the channel may become outflanked at the ends through erosion of the banks.

Single logs can also be used as groyne structures, with the log sloping down from the bank into mid-channel. In such a case the orientation of the log to the channel has a significant impact on local scour and siltation. An upstream orientation results in siltation on both sides of the structure with scour at the mid-channel end, a downstream angled structure will see a tendency for scouring of the upstream bank along with scour at the channel end and siltation on the downstream side.

4.7.1 Post-construction evaluation

The anchoring and stability of the structures have been generally proved over the 1 year of flows to date. Some of the structures have adjusted slightly to cable tightening and local geomorphic developments. The exceptions were the first few emplacements, constructed on Macmillan Creek, which were not adequately buried or anchored with deadmen. The lower arch structures were initially built on the channel surface with no backfilling, and they have remained on the surface with little change to the channel morphology, indicating some flotation may have resulted at high flows.

The anticipated geomorphic development at the structures was generally not achieved in this 1st year of development. The finer storage sediments, especially in Sachs Creek, have eroded from the "storage" logs of the arch structures and this has resulted in underscour and low flows passing

beneath the logs. Although scour pools have formed, their development has not been as extensive as planned.

The structures in Macmillan Creek have been more successful in trapping sediments than in Sachs Creek. This is believed to be a result of the larger size of the substrate, with the boulder sizes having become lodged behind the storage logs and progressively trapping finer materials upstream.

Sediment washing from under the storage logs is believed to have been caused by a combination of high velocity flows and disturbance of the gravels from spawning salmon. A solution to the problem is to provide support for the storage sediment with large cobbles and boulders (if present) or branches and smaller logs where the bed sediments are gravel or fine cobble.

The single log structures generally performed better than the arches from a geomorphic perspective, with storage of sediments upstream and the creation of large scour pools downstream. The exception has been where logs were placed approximately horizontal. In these cases, low flows now pass under the logs and defeat their purpose. The recommended placement for single log structures is to have the log angled down from the bank, with the mid-channel end pointing upstream and buried into the bed.

5 RESTORATION GUIDELINES

Streams destabilized by mass wasting will remain in a state of constant change until sediment sources and in-channel processes stabilize. Thus, it is arguable that a 1-year post-construction evaluation can adequately document the performance of design features requiring a full range of winter flood flows to achieve scour and fill objectives. Indeed, some of the structures tested in this study did not reach design goals. However, most stream restoration objectives achievable within 1 year post-construction were met. Log placements were shown to increase the width and depth variability of the channel, pool to riffle ratios were significantly improved, and winter cover characteristics were increased. Use of deadmen, riprapping, and cable anchors were shown to be effective stabilizing techniques in channels lacking natural anchor points and where stream recovery is dependent on restoring stable hydraulic controls.

Some of the structures tested did not perform to "design specifications." Not placing logs deep enough into the bed during the initial construction was a greater problem than originally anticipated. The shallow burial resulted in a number of structures remaining elevated at bed level, causing lateral scour as opposed to sediment storage. At several sites, lack of expected debris complexing by small material on the upstream side of sediment storage logs also prevented the process of infilling and creation of upstream sediment wedges. Of the problems identified during the study, most were related to uncertainties associated with channels still destabilized following disturbance. While in a state of development, gravel scour and aggradation characteristics are difficult to predict, as is anticipating post-construction bed elevations. Time is also an important element. A minimum of several years or major flood events are required to initiate the morphological changes desired with the structures.

In developing the following guidelines, we have concluded that log placements in streams directly affected by mass wasting are an effective restoration procedure that will speed the development of fish habitat. Based on the performance of the most successful structures, we also predict that problems associated with lack of infilling and uncontrolled scour can be minimized during construction through careful attention to log elevations and minor changes in structure design. These and other recommendations are discussed.

Valuable insights to restoration guidelines may be generated through re-assessment of the present structures in a subsequent study, now that the structures have been subject to high flows.

5.1 Project Development

5.1.1 Candidate streams

The techniques examined in this study were developed for use in streams damaged by mass wasting, but are applicable to any situation where development activities or severe flooding has resulted in a loss of stable debris required for creation of summer and winter rearing habitat and gravel stability. Loss of mainstem habitat is most critical in the lower ends of smaller, higher gradient streams where off-channel habitat is limited by channel and flood plain configuration. In these streams, the lack of broad riparian zones or flood plain precludes the development of side channel, pool, or pond

areas. Thus, in many small coastal streams, mainstem log placements or boulder groupings are the only suitable methods for re-establishing the necessary hydraulic controls that are required to develop stable pools and riffles.

Within candidate streams, results of this study suggest restoration activites involving log placements should be limited to stream reach sections with less than 3% gradient. Above this threshold, storm flow velocities can cause excessive underscouring without the development of pools, and structures have reduced capability to store sediments.

5.1.2 Pre-site assessment

Preparation of a 1:250 or 1:500 scale map which describes pre-construction channel characteristics is the most valuable tool used in planning the stream rehabilitation project. The map is used to document the physical characteristics of the channel and to design the structures according to existing channel form, depth, bank, and valley bottom features. The plan view map must be augmented by cross-sectional and thalweg profiles to finalize selection of structures and to determine optimal vertical and horizontal spacing. From the map, accurate estimates of equipment, labour and material and supplies can be calculated from the time estimates provided in this report.

Advice from an experienced hydraulic engineer or fluvial geomorphologist is essential in finalizing the rehabilitation requirements for a given stream. These experts can provide information on anticipated flood flow levels and energy exerted on proposed structures. They can also provide the rehabilitation biologist with valuable advice on stability requirements of individual structures. It is also important that zones of net building and downcutting in a stream be identified by experts so that logs can be placed in the correct vertical position.

5.1.3 Pre-site planning

Each stream situation will be different, but the following relationships will assist the forester in finalizing a project design involving log placements.

Structure spacing

Based on the frequency of cross channel obstructions found in unlogged streams on the Queen Charlotte Islands, the number of cross stream placements in undisturbed channels is approximately one every two bankfull widths (Hogan 1986). This frequency was applied in this study, but, for purposes of maximizing production of fish habitat, it appears we would have benefited from a spacing of approximately one placement for every 1.5 bankfull widths, with consideration to stream gradient. The closer spacing would have achieved a more balanced final pool to riffle ratio and maximized our ability to reduce localized stream gradients through increased frequency of log steps. Individual channel characteristics are the final deciding criteria for determining the actual number of placements

that can go in, but the bankfull width rule is a valuable tool for estimating the maximum number of logs that may be required for a given stream reach section.

Type of structures

Two types of structures were tested in this study, simple cross stream placements and double and triple log arches. The most efficient structure in terms of benefit/cost was the single cross stream log oriented horizontally diagonal to the channel and vertically oblique to the bed. Average construction time from start of the initial excavation to finish was 1.5 hours of machine time and 2.0 hours of manpower. The single log was easiest to place, posed fewer problems in achieving an oblique position to the bed, and was the least difficult to stabilize using cable anchors, deadmen, or riprapping. The double and triple log arches required approximately 3.0 hours to complete a site and posed considerable problems in achieving proper log elevations. Logs positioned too high over the bed did not achieve scour objectives and resulted in minimal gravel storage. Where the arches worked satisfactorily, the complex nature of habitat developed was attractive, but one can achieve an equal level of complexing by cabling rootwads or smaller debris to the downstream side of single log structures. Log arches may be preferable to single logs where the stream is too wide to span with one log. Single log placements are also considerably less vulnerable to forming log or debris jams which can reduce the inherent stability of the structure and interfere with adult fish passage. Although complexing the single log sites with tree tops, root wads, and debris-catching cables would quickly add habitat cover, the benefits would need to be weighed against the risk of causing a log jam.

Log dimensions

Two dimensions are important in achieving scour and fill objectives through log placement: diameter and length. The most manageable logs were those less than 1 m in diameter (0.4-0.6 m). They were the easiest to bury at specified angles, thus minimizing problems of underscouring. The length of the log should preferably span the rooted width of the stream. This minimizes the possibility of flow changes isolating the log and directing the channel away from the site. In situations where logs were insufficient to span the stream, logs were effectively cabled together, thus achieving a greater span.

Depending on area supply, cedar pulp logs are logical candidate materials for a stream restoration project. They are of least value to the forest harvesting company and will do the same job as any other material. However, the buoyancy of cedar and spruce logs must be weighed against the uplift placed on deadman anchors, and the potential displacement of the logs. This may be alleviated if the logs are acquired several months before the project and stored in water to raise the moisture content of the wood. However, if buoyancy is a concern, green or water logged hemlock would be preferred over cedar. Hemlock would also have less tendency to dry out and increase potential buoyancy during low flow periods than would other species.

Equipment and labour requirements

From the average cost data presented in Table 2 and preliminary estimates of the number of sites to be developed, total estimated time to complete a typical project can be calculated. Other considerations also must be included in the final time and cost calculation, such as source and condition of the logs available for use on a given project.

As well, access must be considered in the total costs. Estimates on trucking and getting the logs to the site will be specific to an individual stream. A well-planned project would have the logs hauled to the site by truck, and moved to site-specific locations by a log skidder. The slower, more costly excavator would be used only for excavation and site-specific log work after the bulk of the activities has been completed by the skidder operator. Use of existing streamside timber should also be considered, particularly where costs are an important factor.

Equipment required to undertake log placement work includes:

- excavator (for excavation and log positioning)
- log skidder (for delivering logs to the site)
- chainsaw
- cable cutters (cable is used to anchor logs)
- cable tightening device (come along)
- hand tools (sledge hammer, marlin spike)
- first aid kit
- hard hats

5.1.4 Construction

Specific construction guidelines for single and multiple log structures and off-channel pools are given in Figures 16, 17, and 18. General guidelines relating to access, environmental safety, and equipment are are discussed below.

Sequence

Plan to start construction upstream and work downstream to avoid fine sediments (generated by construction of other sites) accumulating in the new pools at log sites. Also, by working down the stream, the excavator will be positioned downstream of the site and will be less likely to stand in water ponded behind excavated trenches and berms temporarily formed during construction.

Access

Limit machine access, where possible, to overbank areas to protect existing instream habitat. In small streams, particularly those where a flood plain is lacking and activities in riparian areas would

result in destabilizing stream banks, use of the existing channel may be preferable to the overbank areas for access.

Environmental requirements for heavy machinery

It is not permissible to operate heavy machinery that has not been high pressure washed to prevent introduction of fuel, oil, or grease into a stream system. Daily inspection of all machines should be conducted to identify and order repairs to equipment when needed. Backhoes and skidders should not be parked in the channel overnight, but moved to overbank areas. Fueling and lubricating heavy equipment is not permissible within the active stream channel, nor is it permissible to store fuel below the high water mark of the stream.

Fisheries agencies will require work to be restricted to least sensitive time windows, usually during summer low flows.

Personnel safety

Instream rehabilitation activities involve relatively high risk activities that can result in serious accident. All personnel should be required to wear hard hats and hard toed boots, and a good industrial first aid kit should be available.

SINGLE, DIAGONAL LOG

Placement:

Place logs diagonal to the channel and oblique to the streambed to achieve fish passage at all flow levels while promoting desired scour and fill characteristics. Vertical placement should vary with rate of stream downcutting. Bury the upstream end of log flush with original streambed elevation or lower, downstream end with half of log below the bed or lower.

Excavation:

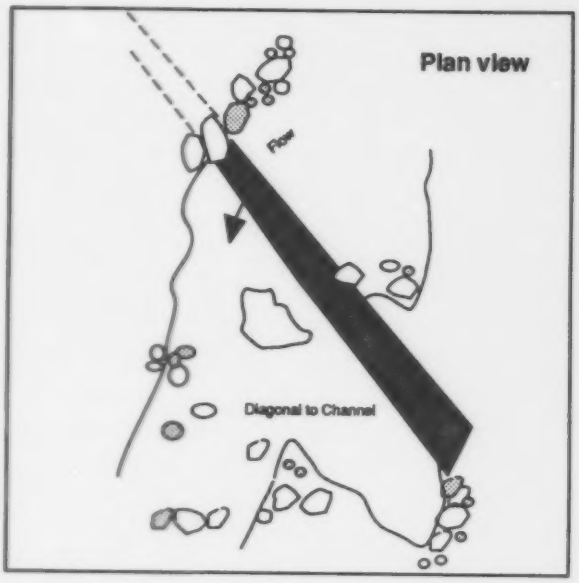
Excavation along the entire log is required to achieve proper elevation with respect to flow levels. The upstream end of the log should be as near to surface elevation as possible. Bury the upstream end of the log up to 1-2 m into the bank to stabilize the upstream portion of the log.

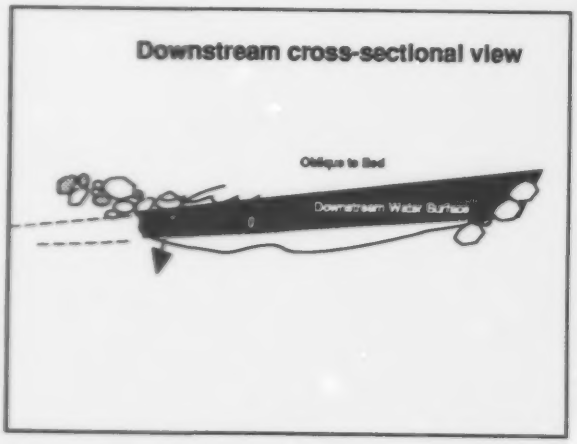
Anchoring:

Anchors are required to stabilize the logs and prevent washing out during flood flows. Anchors can be any stable material (e.g., dead or live trees, boulders, stumps). In the absence of natural anchors, logs can be cabled to deadmen buried into the stream bank or bed. Deadmen can be created from any material. Small logs (2 m in length) buried to a depth of 1.5- 2 m were successful in maintaining the logs in this study where cable ties to overbank materials were not possible.

Scour Characteristics:

Depending on the location where scour is desired, directing the stormflow towards the bank is possible by manipulation of the log's orientation. A log angling to the right, in a downstream direction will direct stormflows to the left. Scour and pool depth should be greatest in the vicinity of the downstream end of the log.





Sediment Storage:

Stream sediment stabilization can be achieved through proper vertical and horizontal orientation of logs. Typically, gravel bars form upstream and downstream of the high end of a log. Problems can arise in achieving storage if stream flow is permitted to flow along or under the downstream butt end of the log. Deposition along the upstream side of a log can be facilitated if screening is positioned along the upstream side and backfilled with material larger in diameter than the screen. Storage areas pre-filled by heavy equipment was often eroded by the first storms until an equilibrium was established.

FIGURE 16. Construction guidelines for single log placements with schematic and plan view maps showing orientation and position of logs relative to a stream channel.

LOG ARCH STRUCTURE

Placement:

Log arches can be constructed from either two logs or two logs with a cross-stream brace as shown. The apex of the main logs is directed upstream and placed in the centre of the channel. As with single log placements, the main logs are positioned oblique to the streambed with log butt ends downstream at bank elevation. Where butt ends can be anchored by cabling the cross brace is not recommended.

Excavation:

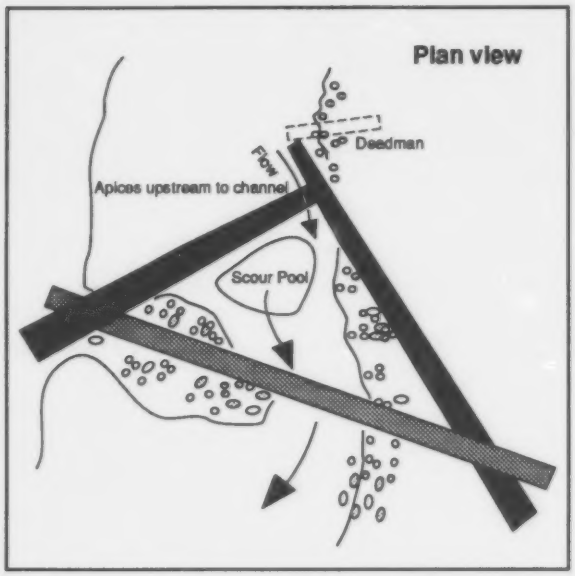
The upstream end of the top main log is excavated into the streambed flush with the bed surface, with the lower main log buried still deeper to ensure juvenile fish passage at all flows. Bury the butt ends downstream half way out of the original streambed. Further excavation is required to bury a deadman 2 m deep at the arch apex.

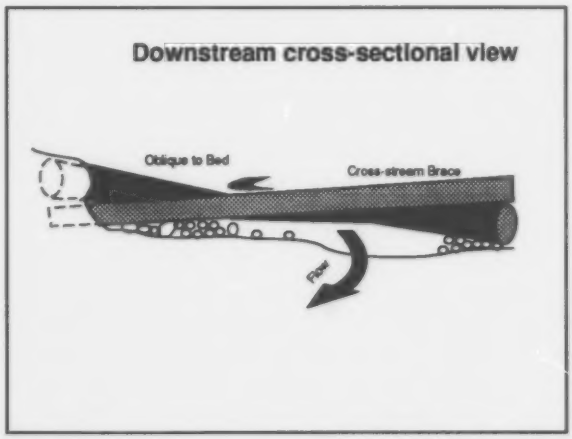
Anchoring:

Cable ties from the outside ends of the main logs are extended to anchors located in overbank areas. It is important to anchor the arch apex to a deadman to prevent the structure from floating during stormflows. Brace logs may be required where bank anchors cannot guarantee stability of the downstream ends of logs.

Scour Characteristics:

A deep plunge pool will develop in the channel centre downstream of the apex. Unless gravel storage backfills the logs, underscouring may assume predominance along the upper logs. Screening as described for single logs would assist in achieving desired deposition.





Sediment Storage:

Gravel bars tend to form upstream and downstream of the high end of main logs with a mid-channel bar upstream of the apex.

FIGURE 17. Construction guidelines for multiple log placements with schematic and plan view maps showing orientation and position of logs relative to a stream channel.

OFF-CHANNEL PONDS

Placement:

Ponds are created in off-channel areas to form deep water summer and overwinter habitat. A succession of ponds up small tributaries form a "beaded channel." Either single holes or elongated double holes can be constructed, separated by shallow riffes. In a continuous line, the upper-most pond will serve as an effective settling basin. When located near a point of access this basin can be periodically emptied.

Excavation:

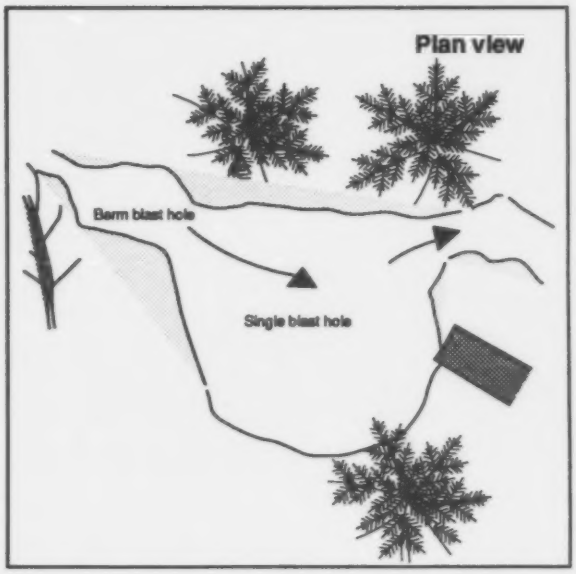
A charge consisting of 75 lb. of Amax ingnited by three sticks of dynamite was capable of producing 2 m deep by 5 m diameter holes in soft streambed materials. In gravels, hole depth may be limited to 1.5 m, depending on amount of charge used. Secondary blasts at the hole periphery are required milliseconds after the main charge to alleviate buildup of a blast berm at the inlet and outlet areas. All blasting must be done by a licensed blaster.

Habitat Complexing:

Blast holes are probably too simple to serve as preferred winter habitat. Complexing the deep water habitat with hand-placed logs, tree tops, or small rootwads is recommended to improve overall cover characteristics.

Site Reclamation:

Vegetation within 1-2 m of the blast hole is either removed, buried, or damaged by the explosion. Site reclamation should include seeding. When involving a forest plantation, reclamation requirements should be reviewed with agency or industry forest managers before the project is initiated.



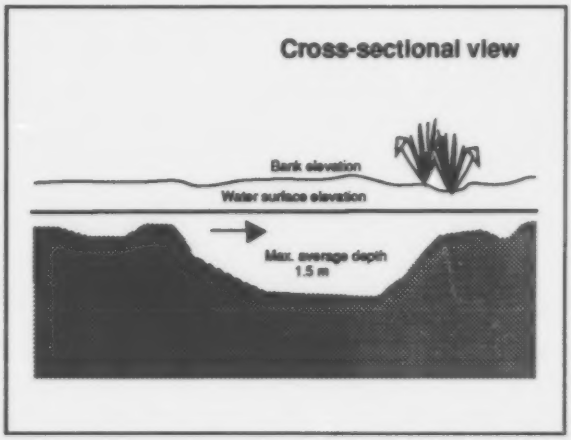


FIGURE 18. Construction guidelines for blast pools with schematic and plan view maps showing size and configuration of pools.

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APPENDIX 1.

Rehabilitation site specifications

SACHS CREEK SITE 1

Placement: Two-log arch placed in tandem with apices directed upstream

Location: 350 m upstream of estuary through glide and shallow riffle habitat

Excavation: At apices of arches to position logs oblique to the streambed and to initiate scour pools; old buried LOD was exposed at upstream apex and incorporated into arch, thus developing a more complex structure

Positioning: Downstream end of logs elevated to sit on top of banks and upstream log angled oblique to the bed. Lowest-most log positioned at surface elevation of the bed with upper log lying on top

Anchoring: Apices of arches cabled to deadmen buried 2.0 m in substrate. Lowest-most set of logs also anchored by deadmen at right bank. Remaining log ends cable lashed to live alder trees on stream bank, and one end to an old blowdown overhanging the stream.

Backfilling: Adjacent to the stream bank of both structures except for the bottom right bank

SACHS CREEK SITE 2

Placement: Three-log arch placed in tandem with apices directed upstream

Location: 1000 m upstream of estuary through glide and shallow riffle habitat situated downstream of large LOD pool

Excavation: Required at apices of arches to position logs oblique to bed and at scour pool locations, and to bury deadmen; several old buried LOD exposed at lower arch

Positioning: Logs elevated to sit on top of banks and angled down so that one log was at streambed surface at the apex with another log lying on top; third brace log positioned on top of both main logs

Anchoring: Logs cabled to deadmen buried 2.0 m, upstream of the apices; all log ends cabled to live alder or spruce trees

Backfilling: Minor amounts upstream of two right bank logs where they met the bank and major filling upstream of the two left bank logs

MACMILLAN CREEK SITE 1

Placement: Single diagonal log

Location: Within estuary adjacent to old root wad at riffle/pool break

Excavation: On left bank upstream of root wad to insert one end of log 2 m into bank, and on right bank to position log vertically

Positioning: Log buried flush with top of right bank; top of left end of log at streambed surface and upstream of right end

Anchoring: Buried 2 m into left bank; cabled to root wad on right

Backfilling: Piled stream boulder riprap on top of right end to prevent log from floating; trench on left bank filled with riprap

MACMILLAN CREEK SITE 2

Placement: Single diagonal log with parallel brace log to support fracture

Location: Limit of tidal influence at glide/riffle break

Excavation: Both ends to position vertically and anchor into bank

Positioning: Flush with stream bank on right bank; flush with streambed on left bank; left end of log upstream of right end

Anchoring: Cabled to old stump on right bank; buried 3 m into left bank

Backfilling: Only to fill trench on top of log on left bank

MACMILLAN CREEK SITE 3

Placement: Three-log arch

Location: 35 m upstream of estuary, mid-riffle

Excavation: For deadman at apex

Positioning: Two main logs lying on streambed with brace log on top

Anchoring: All logs cabled to each other; apex cabled to deadman; downstream ends of main logs cabled to live spruce trees

Backfilling: None

MACMILLAN CREEK SITE 4

Placement: Three-log arch

Location: 60 m upstream of estuary, spanning a lateral scour pool and a glide

Excavation: For deadman at apex; mid-stream portion of left main log

Positioning: Left main log dipping slightly down to apex and below right left log; brace log on top of both main logs

Anchoring: Apex to deadman; distal ends of main logs cabled to stable debris levee material

Backfilling: Left log buried to prevent floating; major deposit created upstream of left log

MACMILLAN CREEK SITE 5

Placement: Three-log arch

Location: 160 m upstream of estuary; mid-riffle

Excavation: For deadman at apex; minor amounts along main logs

Positioning: Right log on top of brace log; brace log on top of left log; left log on top of right log

Anchoring: Apex cabled to deadman; distal ends of main logs cabled to large spruce trees

Backfilling: Minor amounts where main logs attached to banks

MACMILLAN CREEK SITE 6

Placement: Single diagonal log

Location: 190 m upstream of estuary against clay bank

Excavation: On left bank to insert end of log 2 m into stable clay bank, and on right bank to position log vertically

Positioning: Log buried flush with top of right bank; top of left end of log at streambed surface and upstream of right end

Anchoring: Log buried 2 m into left bank; right end anchored with riprap

Backfilling: Piled stream boulder riprap on top of right end to prevent log from floating; trench on left bank filled with riprap

MACMILLAN CREEK SITE 7

Placement: Single diagonal log with brace log to support fracture

Location: 210 m upstream of estuary at head of side channel

Excavation: On left bank to insert end of log 2 m into bank, and on right bank to position log vertically

Positioning: Log buried flush with top of right bank; top of left end of log at streambed surface and upstream of right end

Anchoring: Log buried 2 m into left bank; right end anchored with riprap and cabled to spruce tree

Backfilling: Piled stream boulder riprap on top of both ends to prevent log from floating; trench on left bank filled with riprap

MACMILLAN CREEK SITE 8

Placement: Single diagonal log

Location: 280 m upstream of estuary at head of side channel

Excavation: On right bank to insert end of log 2 m into bank, and on left bank to position log vertically

Positioning: Log buried flush with top of left bank; top of right end of log at streambed surface and upstream of right end

Anchoring: Log buried 2 m into right bank; right end anchored with riprap and cabled to stump

Backfilling: Piled stream boulder riprap on top of left end to prevent log from floating; trench on right bank filled with riprap

MACMILLAN CREEK SITE 9

Placement: Two diagonal logs in tandem (e.g., "<")

Location: 300 m upstream of estuary immediately upstream of large stump

Excavation: On left bank to insert end of downstream log 2 m into bank, and on right bank to position logs vertically

Positioning: Downstream log buried flush with top of right bank; top of left end of downstream log at streambed surface and upstream of right end; downstream end of upstream log on top of downstream log; upstream end of upstream log buried flush with top of right bank

Anchoring: Downstream log buried 2 m into left bank; right end anchored with riprap and cabled to spruce tree; the two logs were cabled together and upstream log right end cabled to spruce tree

Backfilling: Piled stream boulder riprap on top of right ends to prevent log from floating; trench on left bank filled with riprap

MACMILLAN CREEK SITE 10

Placement: Single diagonal log

Location: 340 m upstream of estuary

Excavation: On right bank to insert end of log 1 m into stable clay bank, and on left bank to position log vertically

Positioning: Log buried flush with top of left bank; top of right end of log at streambed surface and downstream of left end

Anchoring: Log buried 1 m into right bank; left end anchored with riprap and cabled to spruce tree

Backfilling: Piled stream boulder riprap on top of left end to prevent log from floating; trench on right bank filled with riprap

MACMILLAN CREEK SITE 11

Placement: Two-log arch

Location: 400 m upstream of estuary in cascade riffle

Excavation: In streambed and left bank to position logs vertically

Positioning: Right log buried flush with streambed upstream at centre and 0.5 m higher than streambed against bank; left log horizontal and on top of right log; left log entirely in flood plain to prevent flow into abandoned side channel

Anchoring: All log ends cabled to trees and anchored with riprap to prevent from floating

Backfilling: Piled stream boulder riprap on top of logs to prevent floating; area upstream and downstream of left log backfilled to block flow down side channel

MACMILLAN CREEK SITE 12

Placement: Single diagonal log

Location: 430 m upstream of estuary in cascade riffle

Excavation: On right bank to insert end of log 2 m into bank, and on right bank to position log vertically

Positioning: Log buried 0.5 m higher than top of left bank; top of right end of log at streambed surface and upstream of left end

Anchoring: Log buried 2 m into right bank; left end anchored with riprap and cabled to stump

Backfilling: Piled stream boulder riprap on top of left end to prevent log from floating; trench on right bank filled with riprap

MACMILLAN CREEK OFF-CHANNEL BLAST POOLS

Placement: Two single ponds forming beaded channel

Location: 200 m upstream of estuary in ephemeral side channel

Excavation: Two main charges of 75 lb. Amax detonated by six sticks of dynamite resulting in craters 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlets and outlets; channel excavated by hand to ensure water flow out of ponds

Positioning: Ponds about 8 m apart and 8 m from main channel

SOUTHBAY DUMP CREEK SITE 1

Placement: Single diagonal log

Location: 400 m upstream of estuary

Excavation: Along log to position vertically

Positioning: Left end of log placed on top of streambed near left bank; bottom of right end of log buried 0.5 m into the streambed against right bank

Anchoring: Right end cabled to stable flood plain debris; left end against large flood plain debris and cabled to alder tree

Backfilling: Piled stream boulder riprap on top of right end to prevent log from floating; extensive backfilling upstream of and on top of left end to divert flow away from left bank

SOUTHBAY DUMP CREEK SITE 2

Placement: Three-log arch reversed with apex downstream and lateral brace to left

Location: 420 m upstream of estuary

Excavation: Along main logs to position vertically; 2 m into left bank for brace log

Positioning: Left end of left log upstream and buried flush with stream bank near left bank; right end of left log placed on top of streambed; right log placed on top of left log downstream at centre of flood channel; right end of right log upstream and placed on top of streambed; brace log on top of left log and horizontal into bank

Anchoring: Right end of right log cabled to spruce trees; logs cabled together at apex; left end of left log cabled to alder tree; brace log cabled to left log and buried into left bank

Backfilling: Piled stream boulder riprap on top of brace log; extensive backfilling downstream of and on top of left main log to divert flow away from left bank

SOUTHBAY DUMP CREEK SITE 3

Placement: Two-log arch with third log parallel to left log

Location: 440 m upstream of estuary

Excavation: For deadman at apex; along logs to position vertically

Positioning: Right log upstream buried flush with streambed at centre of channel; downstream end of right log on top of stream bank against natural debris jam in centre of flood channel; centre end of upstream left log placed on top of right log; bottom of left end of log placed on top of streambed; downstream left log spans channel, buried into stream bank under right log and buried halfway into streambed against left bank

Anchoring: Apex cabled together and to deadman; downstream end of right log cabled to downstream left log and buried with riprap; left ends of left logs cabled to alder trees and buried with riprap

Backfilling: Piled stream boulder riprap on top of right log to prevent log from floating; extensive backfilling upstream of and on top of left logs end to divert flow away from left bank

SOUTHBAY DUMP CREEK SITE 4

Placement: Two-log arch

Location: 470 m upstream of estuary

Excavation: For deadman at apex; 2-m trench into left bank; along logs to position vertically

Positioning: Left end of left log buried downstream into left bank, flush with streambed; right end of log buried 0.5 m into the flood channel; apex in centre of flood plain; right log placed on top of left log; right log on top of flood plain

Anchoring: Apex cabled together and to deadman; downstream end of right log cabled to alder trees; downstream end of left log buried into left bank and cabled to spruce tree

Backfilling: Filled trench on left bank; piled riprap on top of right end of left log

SOUTHBAY DUMP CREEK SITE 5

Placement: Single diagonal log

Location: 530 m upstream of estuary in cascade riffle

Excavation: 2-m trench into right bank; along log to position vertically

Positioning: Left end of log placed on top of streambed near left bank; right end of log buried flush with streambed into right bank

Anchoring: Left end cabled to spruce tree; left end against large flood plain debris and cabled to alder tree

Backfilling: Filled trench on right bank; piled stream boulder riprap on top of right end to prevent log from floating

SOUTHBAY DUMP CREEK SITE 6

Placement: Two diagonal logs in tandem (e.g., "<")

Location: 540 m upstream of estuary straddling a large stump

Excavation: Along logs to position vertically

Positioning: Downstream log buried flush with top of right bank; upstream left end of downstream log at streambed surface and downstream of large stump; downstream end of upstream flush with streambed upstream of stump; upstream end of upstream log buried flush with top of right bank

Anchoring: Riprap piled on both log and cabled to alder trees on right and to instream stump on left

Backfilling: Piled stream boulder riprap on top of right ends to prevent logs from floating

SOUTHBAY DUMP CREEK OFF-CHANNEL BLAST POOLS

Placement: Two single ponds forming beaded channel

Location: 430 m upstream of estuary in side channel

Excavation: Two main charges of 75 lb. Amax detonated by six sticks of dynamite resulting in craters 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlets and outlets; channel excavated by hand to ensure water flow out of ponds

Positioning: Ponds about 5 m apart and 10 m from main channel

BONANZA CREEK TRIBUTARY SITE 1

Placement: Single pond

Location: ~700-800 m upstream of confluence, ~ 50 m downstream of 1982 "Poulin Pond"

Excavation: Main charge of 75 lb. Amax detonated by three sticks of dynamite resulting in crater 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet. See Figure 14 for plan view.

BONANZA CREEK TRIBUTARY SITE 2

Placement: Single pond

Location: ~70 m downstream of Site 1

Excavation: Main charge of ~75-100 lb. Amax detonated by three sticks of dynamite resulting in crater 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet. See Appendix 3a for a plan view map of the site.

BONANZA CREEK TRIBUTARY SITE 3

Placement: Single pond

Location: ~80 m downstream of Site 2

Excavation: Main charge of ~75 lb. Amax detonated by three sticks of dynamite resulting in crater 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet. See Appendix 3b for a plan view map of the site.

BONANZA CREEK TRIBUTARY SITE 4

Placement: Double pond

Location: ~80 m downstream of Site 3

Excavation: Main charges of 75 lb. Amax and 50 lb. Amax positioned ~5 m apart detonated by three sticks of dynamite resulting in elongated crater 5 m x 10 m by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet. See Appendix 3c for a plan view map of the site.

BONANZA CREEK TRIBUTARY SITE 5

Placement: Single pond

Location: ~80 m downstream of Site 4.

Excavation: Main charge of ~75 lb. Amax detonated by three sticks of dynamite resulting in crater 5 m diam by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet.

BONANZA CREEK TRIBUTARY SITE 6

Placement: Double pond

Location: ~60 m downstream of Site 5

Excavation: Main charges of 75 lb. Amax and 50 lb. Amax positioned ~5 m apart detonated by three sticks of dynamite resulting in elongated crater 5 x 10 m by 2 m deep; two secondary blasts of two sticks of dynamite and 25 lb. Amax to remove berm from channel inlet and outlet.

APPENDIX 2.
Gravel composition analysis

A2a Summary of the first F-test analysis of gravel parameter values for Sachs, Macmillan, and Southbay Dump creeks 87
A2b Summary of the second F-test analysis of gravel parameter values for Sachs, Macmillan, and Southbay Dump creeks 88

In analyzing the gravel quality parameters for this study, the following conventions are adopted in referring to samples or sample groups:

- Year: refers to all samples taken in 1 year. Variations between 1986 and 1987 year samples will measure the primary effect of structure emplacement on gravel character and is the principal desired result.
- Site: refers to samples taken with reference to an individual structure or structure group; that is, the structures define study sites.
- Transect: defines samples taken on a single cross-section line of the river, upstream, between, or downstream of the structures at a site.
- Position: defines the location of individual samples on the transect line.

No replicates were taken at the individual positions in this study. It is well known that gravel texture varies systematically downstream (i.e., between sites in this study), and that it may vary substantially and systematically across a channel section (i.e., between positions in this study). Both effects are consequences of the hydraulic control of sedimentation. These effects must be discounted before the primary "year" effect and the secondary local effects around particular structures, measured by transects, can be discovered. To achieve this, components of variance analysis were carried out which isolated the contributions of year, site, transect, and position. Because there are no replicates, this cannot all be achieved in a single analysis. In the first analysis, variance was divided as follows:

- Year
- Site
- Year x site
- Transect (site)
- Position, declared residual.

The results are shown in Table A2a.

The design is mixed; years and sites are crossed, and transects are nested within sites. Positions within transects are declared to be residual; that is, cross-section variations in sediment characteristics are considered to be non-systematic and to provide a measure of random variation against which to measure the variation in other factors.

The order of testing is as follows:

i. Transect versus position: if transect is not significant the two variances are combined to obtain a new estimate of residual variance;

ii. Year x site versus residual: if the cross effect is not significant, the two variances are combined to obtain a new estimate of residual variance;

iii. Site effect (not of direct interest);

iv. Year effect.

The primary (year) effect is not significant in any analysis except permeability and dissolved oxygen in Sachs and Southbay Dump creeks, and percent<0.85 mm in Macmillan Creek. The DO effects probably are an artifact of surface water DO variation at different sampling times. The permeability effects are contradictory, and the 0.85 effect barely significant. There is no usefully interpretable pattern of primary change. Site and cross effects are highly significant in Sachs Creek. This probably reflects the long-established structures at two sites versus control (no structure actually installed) at two others. Similarly, the transects are significant here. The weakest effect is the 0.85 criterion, probably because the highly energetic streamflow keeps total values very low (<10% of -25.4 mm material).

To eliminate the strong site effects, a second analysis was conducted. In this analysis, position along the channel was chosen as the residual parameter. To eliminate site effects, the data were standardized by site. That is, they were transformed by:

$$\bar{X}_{ijk} = \frac{x_{ijk} - \bar{x}_i}{s_i} \quad ; j=1,2(3); k = 1,3(5)$$

where i indicates the i^{th} site, j is the j^{th} transect within the site, and k is the k^{th} position. The mean and standard deviation are taken over all observations in the site.

The design is now:

- Year
- Transect
- Year x transect
- Position (transect)
- Site as the residual.

Results are given in Table A2b.

In this analysis, the pattern of significant effects in Sachs Creek is absent, probably because downstream site effects have been eliminated. Otherwise, the results essentially duplicate those of the first analysis. Insofar as the main year effect on texture goes, it is entirely nonsignificant. Results on permeability are unfavourable, but not very consistent. It is likely that the trial will have to continue for several years before definitive results appear.

TABLE A2a. Summary of the first F-test analysis of gravel parameter values for Sachs, Macmillan and Southbay Dump creeks

First analysis	D_{50}[a]	D[b]	<3.36 mm	<0.85 mm	Fredle	Permeability	DO[c]
Sachs Creek							
Transect	0.01	0.01	0.10	n.s.	0.01	0.01	0.01
Cross	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Site	0.01	0.01	0.01	0.05	0.01	0.01	0.01
Year	n. s.	n.s.	n.s.	n.s.	n.s.	0.05>	0.01<
Macmillan Creek							
Transect	0.01	0.01	0.05	0.05	n.s.	n.s.	0.10
Cross	n.s.	n.s.	n.s.	n.s.	n.s.	0.05	n.s.
Site	n.s.	n.s.	n.s.	0.05	n.s.	0.10	n.s.
Year	n. s.	n.s.	n.s.	0.10<	n.s.	n.s.	n.s.
Southbay Dump Creek							
Transect	n.s.	n.s.	n.s.	n.s.	n.s.	0.10	n.s.
Cross	n.s.	n.s.	0.10	n.s.	n.s.	0.10	n.s.
Site	n.s.	n.s.	0.10	n.s.	n.s.	n.s.	n.s.
Year	n. s.	n.s.	n.s.	n.s.	n.s.	0.10<	0.01<

Tabular entries indicate significance level in an F-test. Tests were conducted for 0.10, 0.05, and 0.01 levels. For values with significant primary effects, < means values dropped and > means values increased from 1986 to 1987.

[a] Median particle size.

[b] Mean particle size.

[c] Intragravel dissolved oxygen.

TABLE A2b. Summary of the second F-test analysis of gravel parameter values for Sachs, Macmillan and Southbay Dump creeks

Second analysis	D_{50}[a]	D[b]	<3.36 mm	<0.85 mm	Fredle	Permeability	DO[c]
Sachs Creek							
Position	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Cross	0.10	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Transect	n.s.	n.s.	n.s.	n.s.	n.s.	0.01	0.01
Year	n. s.	n.s.	n.s.	n.s.	0.10<	n.s.	0.01<
Macmillan Creek							
Position	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Cross	0.05	0.05	0.10	n.s.	n.s.	n.s.	n.s.
Transect	n.s.	n.s.	n.s.	n.s.	n.s.	0.01	0.05
Year	n. s.	n.s.	n.s.	n.s.*	n.s.	n.s.	n.s.
Southbay Dump Creek							
Position	n.s.	0.10	n.s.	0.05	n.s.	0.10	n.s.
Cross	n.s.	n.s.	n.s.	n.s.	n.s.	0.01	0.10*
Transect	n.s.	n.s.	n.s.	0.05	n.s.	0.05	n.s.
Year	n. s.	n.s.	n.s.	0.10<	n.s.	0.05<	0.01<

Tabular entries indicate significance level in an F-test. Tests were conducted for 0.10, 0.05, and 0.01 levels. For values with significant primary effects, < means values dropped and > means values increased from 1986 to 1987. (*) = very nearly equal to the 0.10 level criterion.

[a] Median particle size.

[b] Mean particle size.

[c] Intragravel dissolved oxygen.

APPENDIX 3.
Plan view examples of blast pools

A3a One-year post-construction plan view map of Blast Pool Site 2, Bonanza Creek, August 1987 90

A3b One-year post-construction plan view map of Blast Pool Site 3, Bonanza Creek, August 1987 90

A3c One-year post-construction plan view map of Blast Pool Site 4, Bonanza Creek, August 1987 91

A3d Five-year post-construction plan view map of 1982 Poulin Pond, Bonanza Creek, August 1987 91

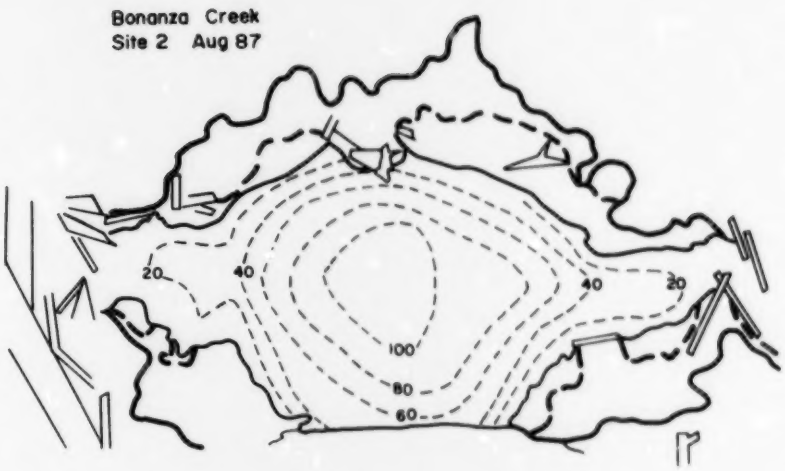

FIGURE A3a. One-year post-construction plan view map of Blast Pool Site 2, Bonanza Creek, August 1987. Depth contours in centimetres. Pool diameter approximately 5 m.

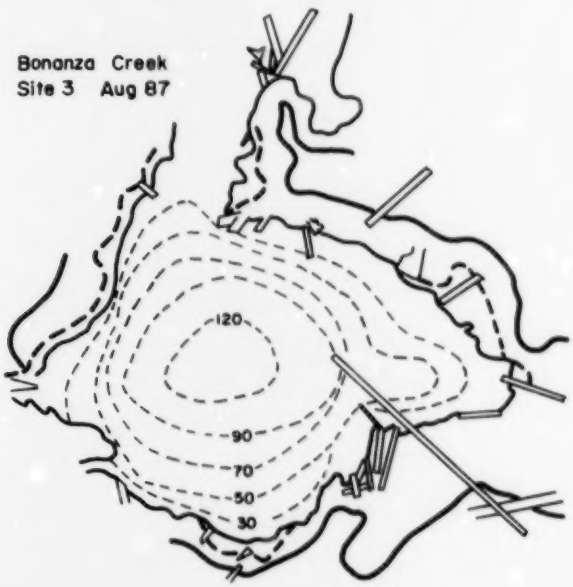

FIGURE A3b. One-year post-construction plan view map of Blast Pool Site 3, Bonanza Creek, August 1987. Depth contours in centimetres. Pool diameter approximately 5 m.

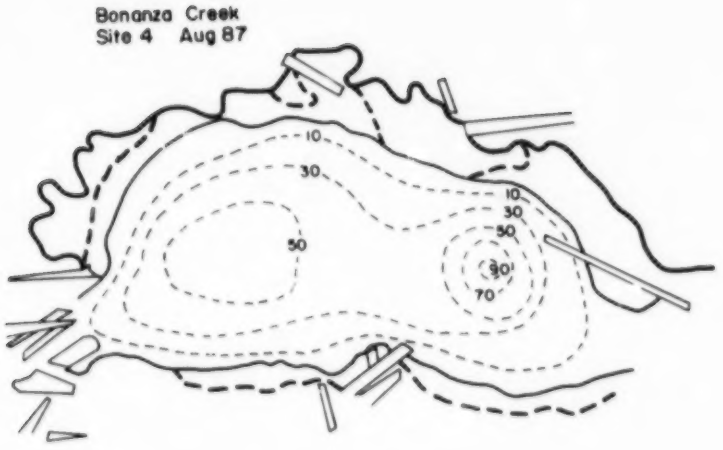

FIGURE A3c. One-year post-construction plan view map of Blast Pool Site 4, Bonanza Creek, August 1987. Depth contours in centimetres. Pool diameter approximately 5 m.

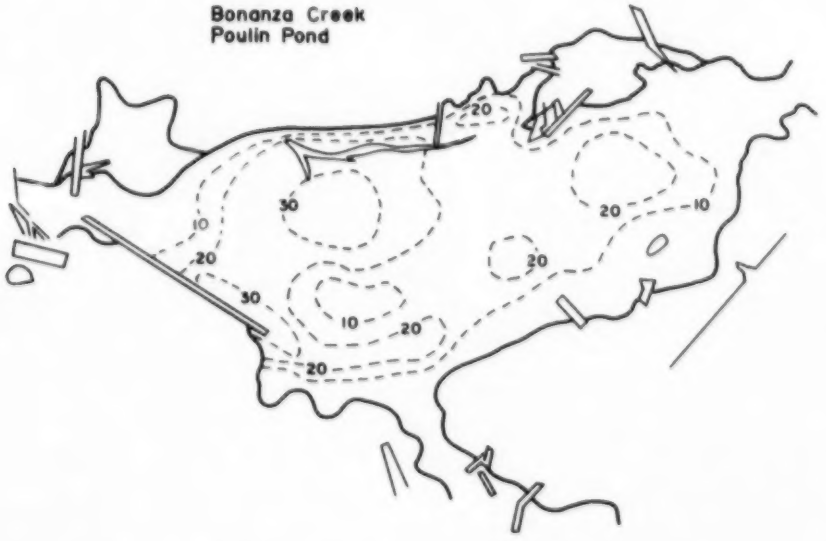

FIGURE A3d. Five-year post-construction plan view map of 1982 Poulin Pond, Bonanza Creek, August 1987. Depth contours in centimetres. Pool diameter approximately 5 m.

APPENDIX 4.
Comparative survey of rehabilitation structures and their streambed configurations three winters after construction

A4a Third winter post-construction summary of pool and sediment configurations, and structure durability at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989 94

A4b Pool abundance at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989 94

A4c Pool area at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989 95

A4d Sediment storage area at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989 96

A4e Stream bank erosion at log emplacements in Macmillan, Southbay Dump, and Sachs creeks, February 1989 96

A4f Durability of log emplacements at Macmillan, Southbay Dump, and Sachs creeks, February 1989 97

A4g Underscour at multiple-log arches in Sachs Creek and in Macmillan Creek, March 1989 98

A4h Single log emplacements in Southbay Dump Creek and in Macmillan Creek, March 1989 99

A survey conducted in February 1989 compared streambed configurations and rehabilitation structure durability of LOD emplacements in Macmillan, Southbay Dump, and Sachs creeks as a component of another operational stream rehabilitation trial.[3] A series of bankfull discharges in fall 1988 subjected the structures to stresses required to generate the streambed configurations that the sites were designed to create. Results of this survey provided a valuable but cursory follow-up to the present study. Another more detailed follow-up study would be in order to provide an evaluation to the level which the initial study was designed and conducted.

The February 1989 survey consisted of measuring representative physical parameters that summarized streambed configurations and structure stability. Streambed configurations were represented by counting the number of pools per log (upstream and downstream), measuring their length and width to calculate the pool area, measuring the length and width, and calculating the area of sediment storage areas. Sediment storage areas were defined as gravel bars associated with the structures that were above water level at time of surveying during winter low flows. Structure stability was indicated by whether a log had moved since construction. The length of eroded stream bank upstream and downstream of the structures was also measured as an indication of stream bank integrity.

Parameter values were summarized on a "per log" basis (Table A4a) rather than "per structure" to provide a more valid comparison between streams having variable proportions of multiple-log arches. Values from upstream of logs were compared to those downstream of logs.

Pools were well developed at log emplacements. On average, between 0.69 and 1.40 pools were associated per log (Figure A4b). Pools tended to be more abundant downstream of the logs than upstream except in Sachs Creek where the number of pools was the same on both sides of the logs. In the higher gradient Macmillan and Southbay Dump creeks, the pools formed were usually plunge pools. In the lower gradient Sachs Creek, the pools tended to be underscour pools. The area of pool per log varied between streams from 4.4 m^2 per log in the smaller Southbay Dump Creek to 20.6 m^2 per log in the lower gradient and larger Sachs Creek (Figure A4c). The pools downstream of logs comprised a larger area than pools upstream of logs in all streams.

The side channel blast pools at Macmillan and Southbay Dump creeks underwent substantial changes since construction. The diameter of the pools remained unchanged since 1986 (4 - 5.5 m), probably from the effective grass/legume cover seeded on the steep banks, keeping them from sloughing into the pools. However, the depth of the pools had decreased substantially. At Macmillan Creek the depths decreased to 35 cm and 50 cm from 95 cm and 101 cm, respectively, and at Southbay Dump Creek the depths decreased to 21 cm and 29 cm from 91 cm and 108 cm, respectively. The blast pools acted as settling ponds, catching fines flowing down the side channels, and subsequently filled in. This process was observed during the survey at Macmillan Creek, with surface runoff from a nearby logging road

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3 Klassen, H.D. 1989. Operational stream rehabilitation trial at Clint Creek, Sewell Inlet. B.C. Min. For., Land Manage. Rep. series. In prep.

TABLE A4a. Third winter post-construction summary of pool and sediment configurations, and structure durability at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989

Stream	No. of logs	Position	Pools				Sed. storage		Bank erosion	Structure integrity		
			No.	No. per log (%)	Area (m^2)	Area per log (m^2/log)	Area (m^2)	Area per log (m^2/log)	per log (m/log)	Stable (%)	Buried (%)	Under-scoured (%)
Macmillan		Upstream	7	37	38	2.0	300	15.8	0.3			
(1986)		Downstream	17	89	111	5.8	271	14.3	3.7			
	19	Total	21	110	149	7.8	571	30.1	4.0	74	5	21
Southbay		Upstream	2	15	6	0.5	215	16.5	0.3			
Dump		Downstream	7	54	51	3.9	104	8.0	1.6			
(1988)	13	Total	9	69	57	4.4	319	24.5	1.9	85	15	23
Sachs		Upstream	7	70	89	8.9	34	3.4	2.5			
(1988)		Downstream	7	70	117	11.7	147	14.7	5.2			
	10	Total	14	140	206	20.6	181	18.1	7.7	70	0	50

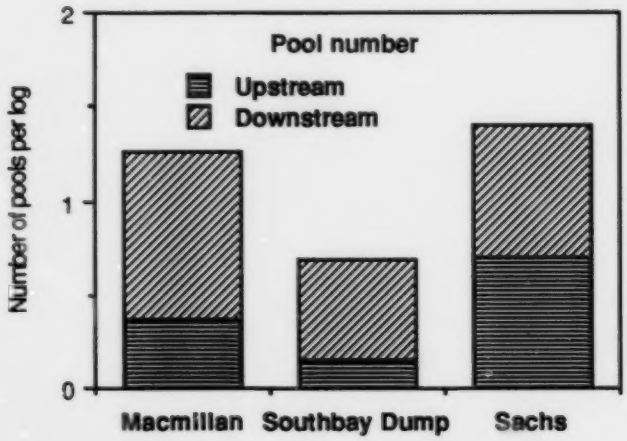

FIGURE A4b. Pool abundance at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989.

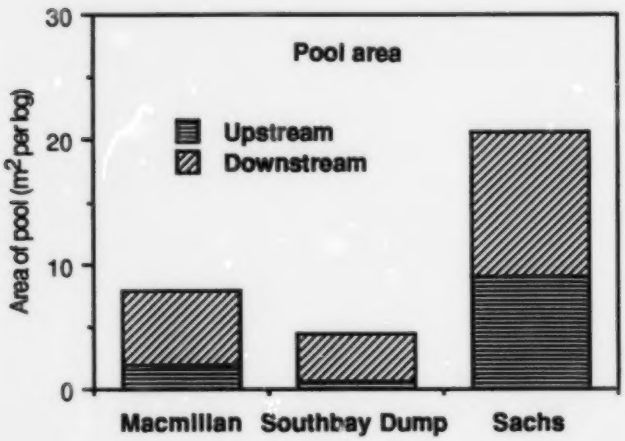

FIGURE A4c. Pool area at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989.

entering the side channel blast pools. The upstream pool was turbid with suspended road sediments, while the pool immediately downstream was relatively clear. Pools at the downstream end of a long series may therefore have a longer effective life than those further upstream.

Sediment storage areas were well developed at log emplacements. On average, between 18.1 m^2 and 30.1 m^2 of sediment storage area was associated per log (Figure A4d). Sediment storage areas tended to be more abundant upstream of the logs than downstream except in lower gradient Sachs Creek, which had substantially more sediment storage downstream of the logs. This contrasted pool development, being predominantly downstream of the logs in the higher gradient Macmillan and Southbay Dump creeks.

Stream bank erosion at log emplacements was evident in all three study streams, averaging between 1.9 m per log and 7.7 m per log (Figure A4e). Stream bank erosion occurred more frequently downstream of the log emplacements than upstream. Erosion was often characterized by the undercutting of stream banks, and it generated additional rearing habitat. Occasionally young alder trees toppled into the stream channel from bank undercutting and added more rearing cover. Sediment entrainment from bank erosion probably occurred during peak flows, and joined an already sediment-laden discharge with little additional effect on fish.

The durability of the log emplacements was generally high. Averages of between 70 and 85% of logs had not moved since placement (Figure A4f). Those that did move were often components of multiple-log arches and shifted less than 1 m. Over bank anchoring cables for the majority of the logs remained slack, suggesting that appropriate levels of backfilling and riprapping for the size and depth of log placements were achieved during construction.

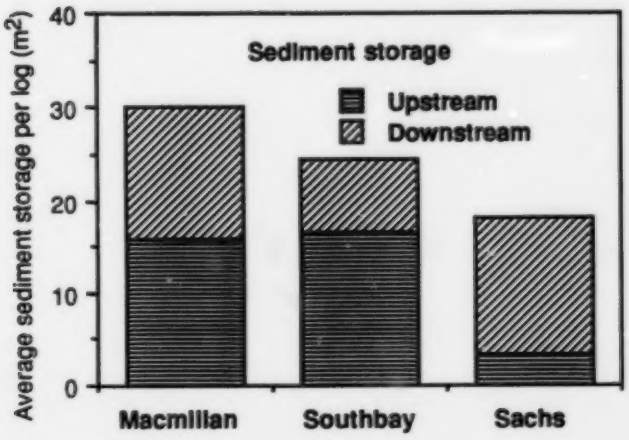

FIGURE A4d. Sediment storage area at rehabilitation sites in Macmillan, Southbay Dump, and Sachs creeks, February 1989.

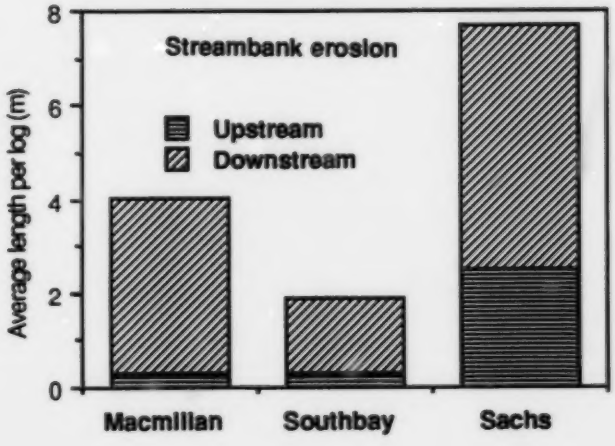

FIGURE A4e. Stream bank erosion at log emplacements in Macmillan, Southbay Dump, and Sachs creeks, February 1989.

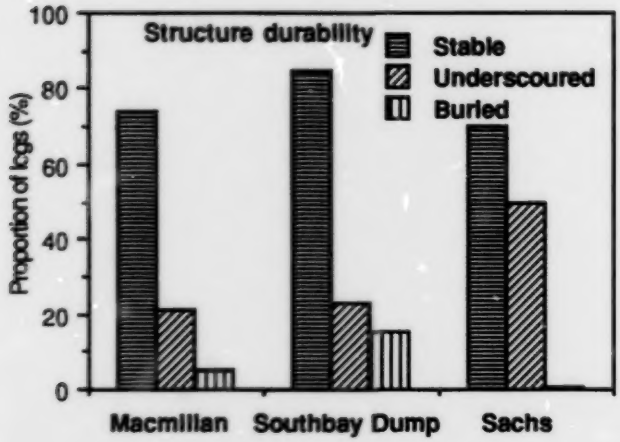

FIGURE A4f. Durability of log emplacements at Macmillan, Southbay Dump, and Sachs creeks, February 1989.

Sediment lobe movement was evident in all three streams. In Macmillan Creek, downcutting in the control region upstream of Site 7 resulted in mobilization of sediments that infilled around the next four sites downstream. A total of 5% of the logs in Macmillan Creek were effectively buried (Figure A4f). In Southbay Dump Creek, remobilization of debris torrent sediments buried 15% of the log emplacements. In Sachs Creek, a log jam failure over winter 1986-87 released a sediment lobe which has migrated into the lower two study sites, but no logs were buried. The generally active channels of torrented Queen Charlotte Islands streams leads one to expect a certain portion of log emplacements may be buried at any given time.

Although substantial sediment storage areas were associated with the logs, considerable underscouring was also observed with averages ranging between 21 and 50% of the logs (Figure A4f). Underscouring developed where the stream flow eroded sediments pre-filled in front of the logs, resulting in flow under rather than over logs. Underscouring was often associated with multiple-log arches where the top logs or logs with ends raking steeply onto the stream bank were placed relatively high in the channel (Plate A4g). The highest degree of underscouring was observed in Sachs Creek where all logs placed were components of multiple-log arches. Minimal underscouring was observed with single, small-diameter logs placed at a shallow vertical angles oblique to the streambed, with the lower end buried well into the streambed (Plate A4h). In studies elsewhere, screen fencing material placed on the upstream of logs effectively prevented erosion of sediments under the log (King 1988).

Although many logs were underscoured, underscouring was not considereded as negative. The pools that formed by underscouring logs appeared effective as juvenile rearing habitat, and particularly effective as adult holding areas. Future rehabilitation designs may best manage for all components of the salmon life cycle and include some underscour pools in their plans.

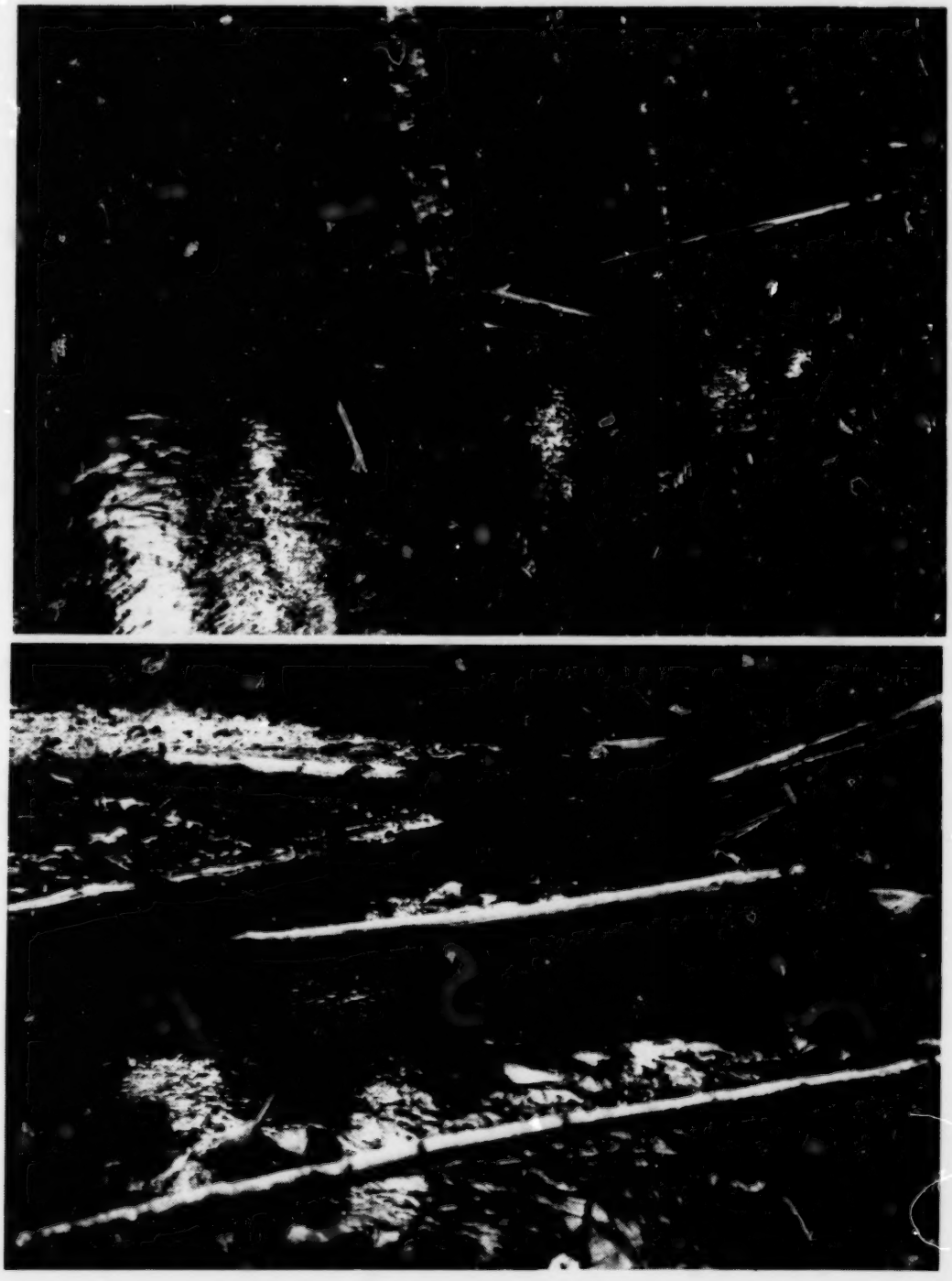

PLATE A4g. Underscour at multiple-log arches in Sachs Creek (above) and in Macmillan Creek (below), March 1989.

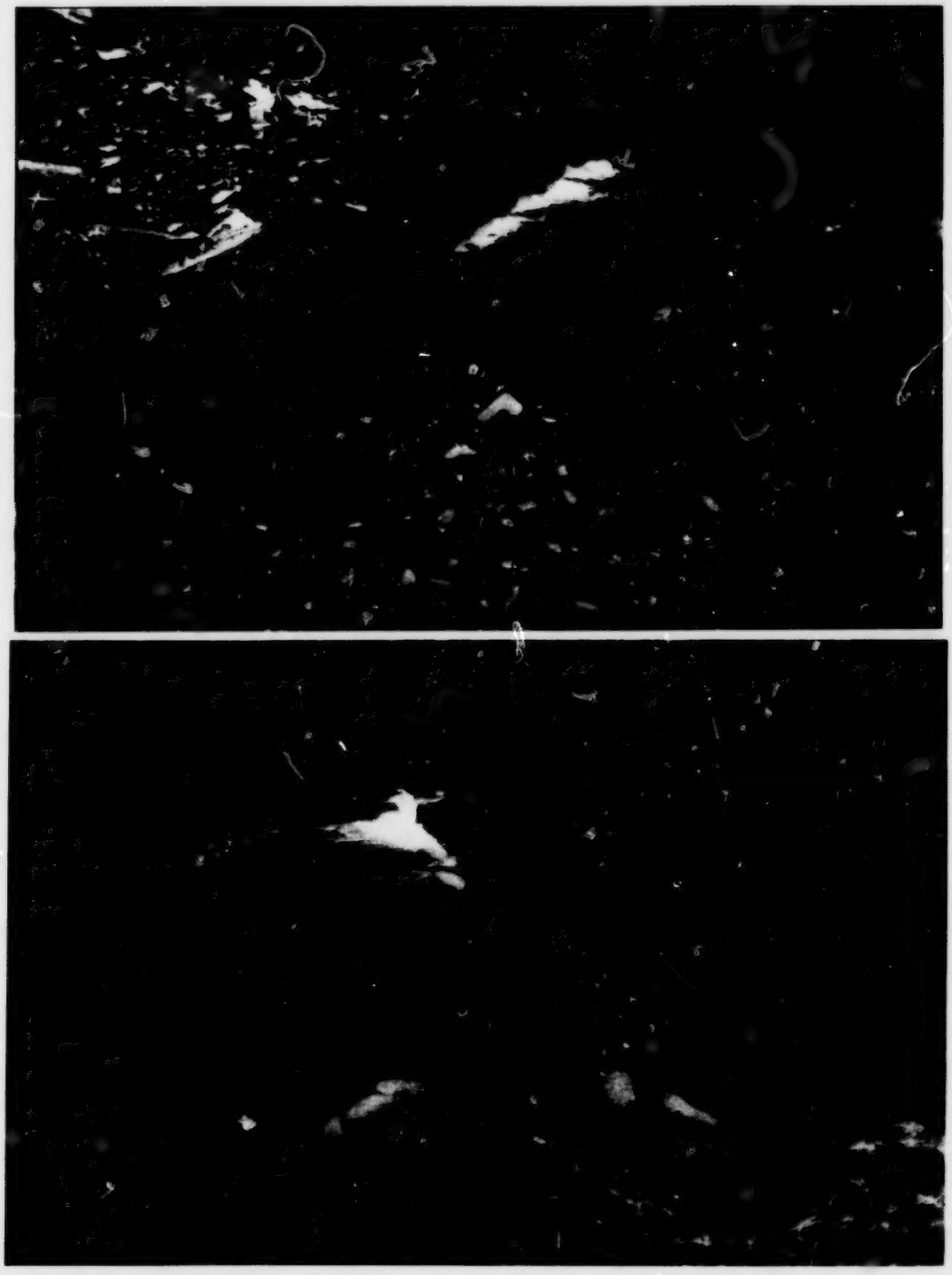

PLATE A4h. Single log emplacements in Southbay Dump Creek (above) and in Macmillan Creek (below), March 1989.